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Computational and experimental study of standing methane edge flames in the two-dimensional axisymmetric counterflow geometry

Giuliano Amantini [a], Jonathan H. Frank [b], Mitchell D. Smooke [a], Alessandro Gomez [a,*]

[a] *Department of Mechanical Engineering, Yale Center for Combustion Studies, Yale University, P.O. Box 208286, New Haven, CT 06520-8286, USA*

[b] *Combustion Research Facility, Sandia National Laboratories, Livermore, CA 94551, USA*

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Abstract

The structure of steady methane/enriched-air edge flames established in an axisymmetric, laminar counterflow configuration was investigated computationally and experimentally. Computationally, the steady-state equations were solved implicitly in a modified vorticity–velocity formulation on a nonstaggered, nonuniform grid, with detailed chemistry and transport. Experimental boundary conditions were chosen to establish flames with a hole centered at the axis of symmetry, the location where the largest strain rate occurs, in order to investigate the structure of the edge flame established at the outer periphery of the hole. Experimentally, CO PLIF, OH PLIF, and an observable proportional to the forward reaction rate (RR) of the reaction $CO + OH \rightarrow CO_2 + H$ were measured. Particle image velocimetry (PIV) was used to characterize the velocity field in the proximity of the fuel and oxidizer nozzles and to provide detailed boundary conditions for the simulations. Qualitatively, the flow field can be partitioned into two zones: a nonreactive counterflow region bound by two recirculation zones attached at the exits of the inlet nozzles, which aid mixing of products and reactants upstream of the edge flame; and a reactive region, where a premixed edge flame provides the stabilization mechanism for a trailing diffusion flame. Comparisons between the experimental and the computational data yielded quantitative agreement for all measured quantities. Further, we investigated the structure of the computational edge flames. We identified the most significant heat-release reactions for each of the flame branches. Finally, we examined correlations among the propagation speed of the edge flame and curvature and mixture fraction gradient by varying the global strain rate of the flame.

Keywords: Edge; Vorticity–velocity formulation; Counterflow; Triple; Diffusion; Premixed; Flame; Computational combustion

1. Introduction

Edge flames have been widely studied in a variety of geometries and flow conditions because of their importance in stabilizing diffusion flames, in the vicinity

* Corresponding author. Fax: +1 (203) 432 7654.
E-mail address: alessandro.gomez@yale.edu (A. Gomez).

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Nomenclature

A	Global strain rate
α	Tangential momentum accommodation coefficient
α_{OH}	Absorption coefficient for OH $Q(12)$
α_T	Dimensionless thermophoretic diffusion factor
δ_m	Mixing layer thickness
div	Divergence operator
D	Particle Brownian diffusivity
D_T	Thermal diffusivity of the mixture
G	Gravitational acceleration
λ	Thermal conduction coefficient
h_k	Total enthalpy for the kth species
$k(T)$	Forward rate constant of the elementary reaction $CO + OH \rightarrow CO_2 + H$
NSPEC	Number of gas-phase species
μ	Dynamic viscosity of the mixture
υ	Momentum diffusivity of the gas mixture
ρ	Density of the mixture
r	Radial coordinate
R	Nozzle radius
RR	Reaction rate of $CO + OH \rightarrow CO_2 + H$
$\vec{t}$	Tangent vector
T	Temperature
$\vec{v}$	Velocity vector
v_r	Radial velocity component
v_z	Axial velocity component
$V_{k,r}$	Diffusion velocity in the radial direction for the kth species
$V_{k,z}$	Diffusion velocity in the axial direction for the kth species
V_T	Local particle drift velocity
χ	Scalar dissipation rate
Y_k	Mass fraction of the kth species
ω	Vorticity
$\dot{\omega}_k$	Production rate for the kth species
Z	Mixture fraction

Subscripts

CH_4	Fuel stream
O_2	Oxidizer stream
p	Particle
FUEL	Fuel stream at the nozzle mouth
OXID	Oxidizer stream at the nozzle mouth
ST	Stoichiometric surface

of surfaces, and in local extinction/ignition phenomena in highly strained turbulent flames. Their ability to anchor diffusion flames [1] by propagating at an effective speed greater than the laminar flame speed [2] is one of their key features.

The counterflow configuration provides a set of well-characterized boundary conditions where edge flames can be analyzed with ease. In this geometry, the entire phenomenology, from a vigorously burning laminar diffusion flame to a locally extinguished flame, can be investigated [3–6].

To understand the genesis of standing edge flames, consider that under conditions of high activation energy chemistry, that is, if the overall chemical reaction is strongly sensitive to temperature, two reaction regimes are possible in the mixing layer between two counterflowing jets of fuel and oxidizer. In the *nearly frozen* regime, mixing occurs without significant chemical reactions, while in the *fast burning* regime the reaction is diffusion-controlled, and the temperature and concentration fields can be qualitatively described using the Burke–Schumann approximation of infinite chemical reaction rate. Extinction, i.e., the transition from the fast burning regime to the frozen one, is abrupt and can be understood in terms of the relative magnitude of two characteristic times: a chemical time, t_c, and a mechanical time, t_m, which can be expressed either as the inverse scalar dissipation rate, $1/\chi_s$, or in terms of the thickness of the mixing layer, δ_m, and the thermal diffusivity, D_T, as δ_m^2/D_T. The ratio of these two times is the Damköhler number, $Da = t_m/t_c = 1/(t_c\chi_s) = \delta_m^2/(t_c D_T)$. In the counterflow geometry, the local value of the Damköhler number is approximately constant in the zone of uniform strain between the nozzles and progressively increases outside this region.

If Da becomes smaller than a critical value, Da_{ext}, then extinction occurs. This condition can be achieved in various ways: (a) by decreasing the mechanical time, through an increase in the strain rate; and (b) by increasing the chemical time, through an increase in the dilution of the feed streams, or by means of a heat sink introduced in the flame. Upon reduction of the local Damköhler number, the flame quenches and propagates outward in the radial direction. This extinction front turns into an ignition front once it exits the nozzle region and stabilizes at a radial location where the local gas velocity equals the speed of the front propagating in the opposite direction in the form of a triple flame [7]. The resulting standing edge flame and the initial unperturbed steady burning diffusion flame can be obtained with the same boundary conditions [8].

Much of the relevant literature on edge flames was reviewed up to 2000 in [9]. Here, we review the relevant edge-flame literature that was published