Available online at www.sciencedirect.com

ScienceDirect

Proceedings of the Combustion Institute 35 (2015) 1305–1312

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

Life of flame particles embedded in premixed flames interacting with near isotropic turbulence

Swetaprovo Chaudhuri *

Department of Aerospace Engineering, National Centre for Combustion Research and Development, Indian Institute of Science, Bangalore 560012, India

Available online 4 September 2014

Abstract

Flame particles are surface points that always remain embedded on, by comoving with a given iso-scalar surface within a flame. Tracking flame particles allow us to study the fate of propagating surface locations uniquely identified throughout their evolution with time. In this work, using Direct Numerical Simulations we study the finite lifetime of such flame particles residing on iso-temperature surfaces of statistically planar H_2–air flames interacting with near-isotropic turbulence. We find that individual flame particles as well as their ensemble, experience progressively increasing tangential straining rate (K_t) and increasing negative curvature (κ) near the end of their lifetime to finally get annihilated. By studying two different turbulent flow conditions, flame particle tracking shows that such tendency of local flame surfaces to be strained and cusped towards pinch-off from the main surface is a rather generic feature, independent of initial conditions, locations and ambient turbulence intensity levels. The evolution of the alignments between the flame surface normals and the principal components of the local straining rates are also tracked. We find that the surface normals initially aligned with the most extensive principal strain rate components, rotate near the end of flame particles' lifetime to enable preferential alignment between the surface tangent and the most extensive principal strain rate component. This could explain the persistently increasing tangential strain rate, sharp negative curvature formation and eventual detachment.

Keywords: Turbulent premixed flame; Surface point; Strain rate; Curvature; Preferential alignment

1. Introduction

A surface point is defined as the following in [1]: "A *surface point* is defined, first, by its location on the surface at a reference initial time t_0; and, second, by the specification that it remains on the surface by moving relative to the fluid (if at all) in the direction of the local normal to the surface". For studying the surface points [2,3], propagating but unconnected, surface elements randomly distributed in non-reacting, isothermal, homogenous isotropic turbulence (NRIHIT) were used to generate the required surface point statistics. Despite very important insights gleaned from these pioneering studies, collectively these surface elements did not form a single physical surface, nor were the surface elements reactive. In particular, in

* Fax: +91 80 23600134.
E-mail addresses: schaudhuri@aero.iisc.ernet.in, swetaprovo@gmail.com

http://dx.doi.org/10.1016/j.proci.2014.08.007

[2,3] the local propagation speed of the surface was modelled to be either linearly dependent on local strain rate or constant. Certainly, the propagation of a true iso-scalar surface within a premixed flame in a turbulent flow could be much more complex. Local flame speed is proportional to the geometric mean of local reaction rate and thermal diffusivity with further non-linear dependence on local strain rate and curvature [4], all of which can be perturbed by the local turbulent flow properties [5]. In non-premixed combustion, mixture fraction surface points governed by a convective–diffusive equation were studied in [6]. To the author's knowledge, motion of surface points embedded in a reacting and propagating isosurface in a turbulent flow have not been studied. Here, possibly for the first time we describe the motion and time history of the characteristic acceleration, straining rate and curvature of surface points embedded in suitably chosen iso-surfaces of initially planar premixed H_2–air flames interacting with oncoming isotropic turbulence. To distinguish between surface points lying on unconnected surface elements in nonreacting flows versus the ones embedded and propagating with the reacting isosurfaces inside a real flame, we will call the latter as *flame particles*. Following the notation used in [1] the flame particle P^F's position vector at a time t is denoted by $\mathbf{X}^F(t)$ where $\mathbf{X}^F(t_0) = \mathbf{X}(x_0, y_0, z_0, t_0)$. Here (x_0, y_0, z_0) is the position of the flame particle at an initial time $t = t_0$. The motion of P^F is given by:

$$\frac{d}{dt}\mathbf{X}^F(t) = \mathbf{U}(\mathbf{X}^F[t], t) + S_d(\mathbf{X}^F[t], t)\mathbf{n}^F(\mathbf{X}^F[t], t) \quad (1)$$

Here $\mathbf{U}(\mathbf{X}^F[t], t)$ is the flow velocity at $\mathbf{X}^F(t)$; $S_d(\mathbf{X}^F[t], t)$ being it's local displacement flame speed and $\mathbf{n}^F(\mathbf{X}^F[t], t)$ the local surface normal at $\mathbf{X}^F(t)$.

With great advances in high performance computing and laser diagnostic capabilities, turbulence-premixed flame interaction mechanisms have been a topic of intense research in recent times [7–18]. In particular, DNS studies [8,9,19,20] have provided important insights on flame topology and turbulence-flame interaction through one time, Eulerian statistics of curvature, strain rates and S_d distributions on the entire iso-surfaces of interest. A semi-Lagrangian technique such as Flame Particle Tracking (FPT) offers a new viewpoint to quantify turbulence-flame interaction by unravelling the time history of individual surface element stretching to annihilation with corresponding change in relevant surface properties. As such, little is known regarding motion of flame particles and their similarity, if any, with fluid particles, surface points or inertial particles in NRIHIT [2,3]. Indeed, strong dependence of S_d on the turbulent strain field and the dilatation caused by heat release can greatly complicate such possible analogy. Furthermore, the constraint that all the flame particles must reside on and comove with the same isosurface at all times, introduces additional inter-particle dependence purely through geometrical considerations. Throughout the paper, the difference between fluid particles and flame particles must always be recognized: the former follows the flow, while the latter follows a reacting iso-scalar surface.

It is indeed important to study the motion of these flame particles for the following reasons: (i) the FPT provides, perhaps the only means to follow a particular position on a reacting surface and any surface relevant property like displacement flame speed, stretch rate, curvature, alignments between strain rates and surface normal, reaction and heat release rates at those unique surface locations, with the evolution of time; (ii) the time history of flame speed and stretch rates of individual flame particles and their ensemble would quantify the persistent/intermittent nature of these quantities on an isosurface inside a turbulent flame; (iii) the fundamental interest to know, how local flame elements accelerate due to the oncoming turbulence and resulting motion in curved paths; (iv) the life and loss of the flame particles could provide very crucial insights on the flame surface fluctuation dissipation/destruction mechanism; (v) Apart from fundamental understanding, FPT could assist in sub-grid scale modelling for Large Eddy Simulations. To model small scale critical processes like local extinction controlled by intermittent strain, with large scale implications like flame blowoff [16,21]; the stochastic flamelet model [22] for Eq. (1) could be utilized. The DNS FPT results could be useful in guiding such modelling efforts.

2. Computations

Direct Numerical Simulation of initially planar premixed flames that get wrinkled by oncoming isotropic turbulence are carried out by the open-source “Pencil code” [23]. This code is designed for solving compressible turbulent flows using sixth order explicit finite difference scheme for spatial discretization and Runge–Kutta type third order scheme for time advancement. Extensive bibliography that has resulted from this code in context of turbulent flows relevant for terrestrial or astrophysical applications could be found in [23]. In [24] combustion chemistry was implemented in the Pencil-code and different classical reaction/flame configurations were extensively validated with widely used Chemkin based packages. The present computations involve an inflow–outflow type configuration characterized by Navier Stokes Characteristic Boundary Conditions