Abstract
Flame Particle Tracking Analysis of Turbulence-Premixed Flame Interaction

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This work describes the computational and theoretical developments made in the understanding of turbulence-premixed flame interaction, using both lean and rich H_2-air mixtures, in a flow field of near-isotropic turbulence. Two classical flame geometries are considered for the present study viz., 1) statistically planar flame in an inflow-outflow channel (type-I) and 2) premixed igniting flame kernel in a box (type-II). These simple geometries, which could be considered as building blocks of turbulent flames in practical combustors, elucidate the intricate physics of turbulence-premixed flame interaction. In the present work, using direct numerical simulations (DNS) and flame particle tracking (FPT) framework, we investigate two cases of turbulent premixed flames: 1) an intensely burning flame, and 2) extinguishing ignition kernels.

The interaction between turbulence, molecular transport, and energy transport coupled with chemistry determine the characteristics of intensely turbulent premixed flames such as the evolution of flame surface geometry, propagation, annihilation, and local extinction/re-ignition. In the first part of the thesis, we describe the turbulence-premixed flame interactions for intensely burning turbulent premixed flames using the type-I configuration. The objective

is to 1) understand the behavior of flame displacement speed (S_d) in the negatively curved regions and/or flame islands, corresponding to two different isotherms (665 K and 1321 K), which eventually dissolve in the product gases, and 2) decipher the role of transport in this behavior. This is carried out by considering lean H_2-air mixtures ($\phi = 0.81$ and $0.7, Le < 1$). DNS computations are performed with different initial conditions and turbulence intensity levels and FPT is used to analyze these Eulerian datasets. An increase in S_d with time for the annihilating regions of isotherms is a common trend observed across four simulation conditions considered. Further investigation reveals that the sharp increase in S_d is due to: 1) heat conduction, 2) increased negative curvature of the flame surface, and 3) eventual homogenization of temperature gradients ($|\boldsymbol{\nabla} T| \rightarrow 0$). The curves of normalized flame displacement speed ($\langle S_d/S_{L,T}\rangle$) vs. stretch rate ($\langle Ka_S\rangle$) in the normalized time for four different cases of turbulence intensity levels collapse on a narrow band for $\phi < 1$, suggesting a unified behavior in the Lagrangian description. Principal curvature evolution statistics show an ellipsoidal geometry for the annihilating flame islands/pockets.

The second part of the thesis addresses the extinction dynamics of igniting kernels in a rich H_2-air ($\phi = 4, Le > 1$) premixture in near-isotropic turbulence. This is accomplished using the configuration of type-II. Here, the analysis procedures, DNS and FPT remain the same as mentioned earlier. Turbulence is found to extinguish a freshly ignited, initially spherical premixed flame kernel, which otherwise sustains in a quiescent flow field by propagating beyond the minimum radius. The mechanism of kernel extinction is investigated by tracking lifetime trajectories of flame particles on an O_2 mass-fraction iso-surface in the flame displacement speed-curvature ($S_d - \kappa$) space using the well-known concept of minimum radius from laminar flames. The classical S-curve in the temperature-Damköhler number ($T - Da$) space was also analyzed. Ensemble-averaged $S_d - \kappa$ and S-curves display corresponding turning points which help to elucidate the intricate mechanisms involved in turbulent ignition kernel extinction dynamics. Turbulence locally wrinkles the Y_{O_2} iso-surface to positively curved structures which lead to turning points in $S_d - \kappa$ space, such that the minimum radius is never reached either locally or as an ensemble. A budget analysis of the principal curvature evolution equation highlights the role of turbulence in *bending* the surface to form positively curved pointed structures where heat loss is enhanced, further lowering Da towards extinction.

The novel Lagrangian viewpoint of flame particle tracking applied on solutions of DNS thus emerges as a powerful tool where turbulence, flame, and their interaction dynamics can be systematically analyzed. These eventually provide unified viewpoints of local flame propagation and flame extinction in turbulence.