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Topologies of Self-Interaction in Turbulent Premixed Flames and Reduced-Order Manifold Models

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When modeled with a reduced-order manifold, premixed flame self-interactions give rise to local extrema in progress variable dissipation rate ($\chi_{\Lambda\Lambda} \equiv 2D\left[\nabla\Lambda \cdot \nabla\Lambda\right] \rightharpoonup 0$) at non-zero/-unity progress variable ($\Lambda \notin \{0, 1\}$). Whether the thermochemical state (T, Y_k) of these self-interaction "critical points" can be captured using a manifold model and whether this depends on the local flame topologies remains unknown. This work demonstrates the ability to replicate the local thermochemical state at flame self-interaction critical points using a manifold model in progress variable Λ by comparing the conditional statistics of Direct Numerical Simulations (DNS) to predictions from the manifold model. A DNS database of premixed statistically planar hydrogen-air flames in moderate turbulence was generated with conditions (similar to [1]) that minimize other forms of local extinction (thermodiffusive instability, cold boundaries, and flammability limits). Extracting local progress variable dissipation rate profiles at the critical points as a function of progress variable $\chi_{\Lambda\Lambda}(\Lambda)$, these profiles are used to close the dissipation rate term in the premixed manifold equations [2]. Further, by accounting for differential diffusion [2], the progress variable curvature $\kappa \equiv \nabla \cdot \hat{n} = \nabla \cdot (\nabla\Lambda/|\nabla\Lambda|)$ was closed in the same manner $\kappa(\Lambda)$. In the limit of vanishing progress variable gradients, the topology of the interaction is also characterized by the scalar Hessian ($\nabla^2\Lambda$) to second-order approximation [3]. This work shows particularly good agreement between manifold model and DNS for important thermochemical scalars and discusses the nature of the progress variable dissipation rate as measure of turbulent mixing in these instances. Finally, the burning velocity at these critical points is evaluated using an analytical model for aerodynamically propagating flame iso-surfaces forming "pockets" and "tunnels" [4].

References

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