Turbulent Combustion Modeling:
A Combustion Perspective and a Turbulence Perspective

Friday, October 13, 2017
4:00 PM Bowen Hall Rm 222

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Turbulent combustion modeling is a challenging multi-physics, multi-scale modeling problem. Both turbulence and combustion are already difficult multi-scale modeling problems, and the combination of the two brings in new interactions across various length scales and time scales that fundamentally change both the combustion processes and the turbulence. However, the prevailing practice in turbulent combustion modeling is to essentially decouple the two phenomena and approach the problem from independent combustion and turbulence modeling perspectives.

Most efforts have focused on the combustion modeling perspective, that is, the modeling of the unresolved, small-scale details of the combustion processes and the many chemical species involved. One common modeling approach is to constrain the underlying combustion processes to reduced-order manifolds by a priori presuming that a single asymptotic “mode”—premixed flame, nonpremixed flame, or homogeneous chemistry—is adequate everywhere. However, turbulent combustion in practical systems is inherently “multi-modal” with the character of the combustion processes varying both in space and in time. As a first step in handling this complexity, we developed modeling approaches that locally identify the most appropriate asymptotic mode. More recently, we developed a new reduced-order manifold approach that captures not only the three asymptotic modes but also intermediate regimes without any significant increase in the theoretical computational cost. The theoretical foundation of this new approach will be discussed, and practical implementational challenges will be identified.

A far less significant effort has been devoted in the turbulent combustion modeling literature to the turbulence perspective, that is, the effects of combustion heat release on turbulence. In fact, most of the turbulence models applied in turbulent combustion modeling are simply adapted from incompressible turbulence, despite previous theoretical arguments that have been made that turbulence is strongly affected by combustion heat release in certain regimes. Through full-fidelity “numerical experiments,” we have identified the regimes in which combustion fundamentally alters the nature of the turbulence. Based on the physical insights from these simulations, we developed new algebraic turbulence models that directly leverage information about the underlying flame structure and qualitatively capture, for the first time in the literature, the effects of combustion heat release on turbulence.

The seminar concludes with a look forward and proposes a completely new framework for a unified approach to turbulent combustion modeling potentially capable of capturing far richer interactions between turbulence and combustion.