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Modeling Interactions Among Turbulence, Gas-Phase Chemistry, Soot and Radiation Using Transported PDF Methods

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The importance of explicitly accounting for the effects of unresolved turbulent fluctuations in Reynolds-averaged and large-eddy simulations of chemically reacting turbulent flows is increasingly recognized. Transported probability density function (PDF) methods have emerged as one of the most promising modeling approaches for this purpose. In particular, PDF methods provide an elegant and effective resolution to the closure problems that arise from averaging or filtering terms that correspond to nonlinear point processes, including chemical reaction source terms and radiative emission. PDF methods traditionally have been associated with studies of turbulence-chemistry interactions in laboratory-scale, atmospheric-pressure, nonluminous, statistically stationary nonpremixed turbulent flames; and Lagrangian particle-based Monte Carlo numerical algorithms have been the predominant method for solving modeled PDF transport equations. Recent advances and trends in PDF methods are reviewed and discussed. These include advances in particle-based algorithms, alternatives to particle-based algorithms (e.g., Eulerian field methods), treatment of combustion regimes beyond low-to-moderate-Damköhler-number nonpremixed systems (e.g., premixed flamelets), extensions to include radiation heat transfer and multiphase systems (e.g., soot and fuel sprays), and the use of PDF methods as the basis for subfilter-scale modeling in large-eddy simulation. Examples are provided that illustrate the utility and effectiveness of PDF methods for physics discovery and for applications to practical combustion systems. These include comparisons of results obtained using the PDF method with those from models that neglect unresolved turbulent fluctuations in composition and temperature in the averaged or filtered chemical source terms and/or the radiation heat transfer source terms. In this way, the effects of turbulence-chemistry-radiation interactions can be isolated and quantified.