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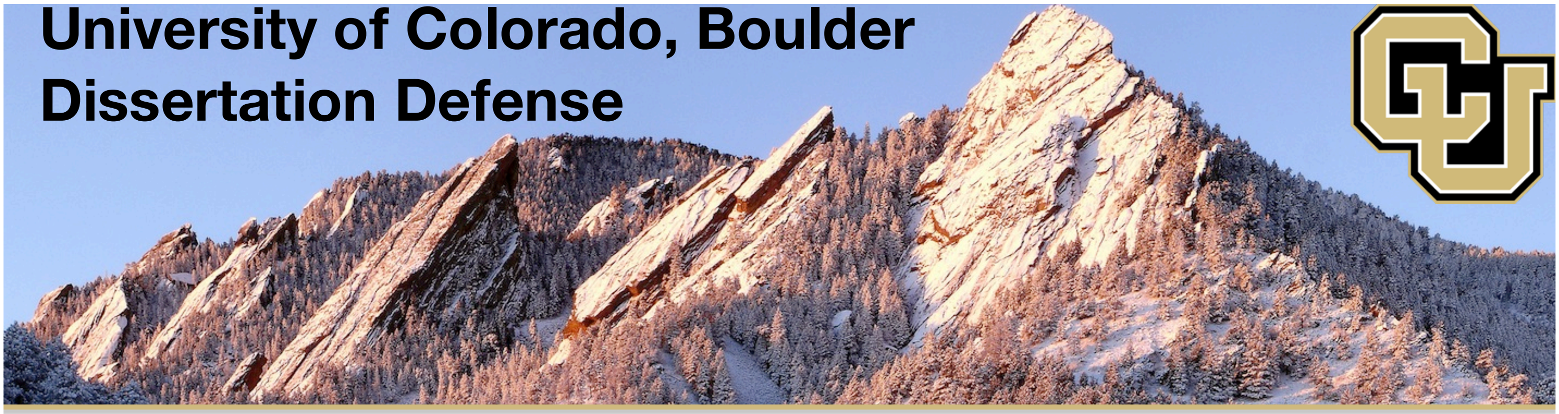

Thursday, January 4, 2017
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Multi-Physics and Multi-Scale Interactions in High-Speed Turbulent Premixed Reacting Flows

Colin A.Z. Towery, *Department of Mechanical Engineering, CU Boulder*

Nonlinear turbulence-chemistry interactions, including spontaneous autoignition and deflagration-to-detonation transition of turbulent reacting flows, play a significant role in the reliability and sustainability of high-speed combustion systems such as scramjet engines, as well as air-breathing and rocket-mode pulsed and rotating detonation engines. In high-speed reacting flows, defined by turbulent velocity fluctuations larger than the relevant laminar flame speed, the reactants are often partially or fully premixed and the turbulence can be non-linearly compressible, wherein turbulent velocity fluctuations directly generate localized shock waves known as eddy shocklets. In order to develop improved SGS turbulence models that can accurately realize turbulence-chemistry interaction phenomena in high-speed turbulent premixed reacting flows, the coupled, nonlinear effects of both premixed flames on turbulent advection and of turbulent advection on premixed flames need to be dynamically quantified and explained. This dissertation examines kinetic energy transfer by advective processes in a turbulent premixed flame in spectral space using data from a direct numerical simulation of a statistically-stationary turbulent premixed flame. Two-dimensional turbulence kinetic energy spectra conditioned on the planar-averaged reactant mass fraction are computed through the flame brush and variations in the spectra are connected to terms in the spectral kinetic energy transport equation. Conditional kinetic energy spectra show that turbulent small-scale motions are suppressed in the burnt combustion products, while the energy content of the mean flow increases. An analysis of spectral kinetic energy transfer further indicates that, contrary to the net down-scale transfer of energy found in the unburnt reactants, advective processes transfer energy from small to large scales in the flame brush close to the products. Triadic interactions calculated through the flame brush show that this net up-scale transfer of energy occurs primarily at spatial scales near the laminar flame thermal width. The present results thus indicate that advective processes in premixed reacting flows contribute to energy backscatter near the scale of the flame.

This dissertation also examines the effects of compressible turbulence thermodynamics on the modes of reaction front propagation under autoignitive conditions, and particularly the conditions required for the localized direct initiation of, or transition to, detonations. Direct numerical simulations of homogeneous isotropic turbulence with both a single-step and a detailed chemical kinetics model are performed at several target turbulence Mach numbers, Ma_t spanning a range of turbulence compressibility regimes. Increasingly broad probability distributions of temperature, dilatation, fuel mass-fraction, and scalar reaction rate are found as Ma_t is increased, indicating that intermittency of quantities relevant to reaction initiation increase as the degree of turbulence compressibility increases. Detailed time histories of Lagrangian fluid parcels computed for Mach 0.2, 0.4, and 0.6 cases reveal that both supersonic and subsonic autoignition reaction fronts can be found in all compressibility regimes, while the formation of detonation and deflagration waves are limited to Ma_t with sufficiently high gradients in ignition delay time, as expected from prior theory and studies of autoignition in externally-imposed temperature inhomogeneities.