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Droplet/ligament modulation of local small-scale turbulence and scalar mixing in a dense fuel spray

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Abstract

In this study, the modulation of turbulence and scalar mixing by finite-size droplets/ligaments in a dense fuel spray is investigated using a DNS (Direct Numerical Simulation) dataset. Ejected from a spray nozzle with a high speed, a liquid-fuel jet deforms and the fuel spray is atomized into many ligaments and droplets. During these processes, the gas flow becomes turbulent due to droplet/ligament dynamics. At the same time, droplet evaporation and mixing with ambient air are affected by the small-scale gas turbulence. An understanding of the mixing characteristics in the dense spray zone is important for modeling spray combustion. In a region where the droplet number density is relatively low, a universal feature of isotropic turbulence was found, although the alignments of strain eigenvectors with vorticity and the mixture fraction gradient are slightly modulated by the presence of droplets, which is a characteristic of particle-laden flows. In gas-phase regions close to droplet surfaces, where the dissipation rate of turbulent kinetic energy is strongly increased, the alignments are more modulated, especially those of the scalar gradient with strain eigenvectors. This can also be seen in the topology similarity among energy dissipation, enstrophy and scalar dissipation in the near field of droplet/ligament surfaces. For the first time, it is found that droplets whose size is comparable to turbulence scales do affect the mixing characteristics in a realistic turbulent spray. This finding has shed new light upon the modeling of flow turbulence and scalar mixing in an evaporating and atomizing fuel spray.

Keywords: DNS; Spray; Turbulence modulation; Scalar mixing; Small-scale structures

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1. Introduction

Liquid-fuel atomization, evaporation, mixing and combustion closely interact with turbulence in spray combustion. The physics is very complex

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since there is a wide range of temporal and spatial scales in an atomizing spray [1–6]. Droplets/ligaments are generated by primary atomization in the near-nozzle region, and the droplet size and distribution subsequently impose a significant impact on the downstream spray dynamics.

In the downstream dilute spray region, the turbulence scale is in general much larger than the droplet scale. While in the dense spray region near the injection nozzle, the turbulence scale is comparable to the droplet scale. For combustion, mixing of fuel/oxidizer is critical. Scalar mixing is strongly affected by small-scale turbulence structures [7–23]. Therefore, when the droplet/ligament size is comparable to the turbulence scale, it is expected that droplets/ligaments would change the small-scale structures, hence mixing. Despite its determining role in the entire spray combustion, droplet/ligament effects on turbulence and scalar mixing in a dense atomizing fuel spray have not been fully understood yet and will be the main objective of the present study.

In turbulent single-phase flows [7–14], correlations between turbulence structures and scalar mixing have been investigated. Abe et al. [14] conducted a DNS study in a heated channel to investigate scalar mixing. At the wall, small-scale structures are dominant due to high strain rates, and are different from those of isotropic turbulence. The small-scale topologies of the vorticity, energy dissipation and scalar dissipation rate become strongly correlated near the wall. Away from the wall, the correlations become weaker and the structures appear more similar to those of isotropic turbulence.

For turbulent multiphase flows, turbulence modulation by liquid droplets or solid particles has been of considerable interest [15–19]. In early studies [15–17], the particle size was much smaller than the turbulence scale, i.e. point particles. Particles, even at a low number density, modify the vorticity dynamics and turbulence production/dissipation rate by the drag force, and the turbulent mass and heat transport [15,16]. The alignments between the vorticity vector and strain eigenvectors are changed as a result of increased dissipation by the particles. Reacting flows laden with point-droplets were investigated by large-eddy simulation [17]. The turbulence modulation was induced by droplets (and heat release) due to the change of the alignments between the strain eigenvectors and the vorticity and also the scalar gradient. The effects of particles, whose size is comparable to the Kolmogorov or Taylor scales, on turbulence are also of interest recently [18,19]. The strain-rate eigenvalue modification was also observed for finite-size particles. In the near field of particles, the increased dissipation rate of turbulent kinetic energy due to the non-slip particle interface can be observed. In most of the studies above, the particles were solid and spherical. In this study, turbulent energy dissipation and heat/mass transport at the surface of deformable droplets/ligaments in a spray configuration are additional physical phenomena.

For simple configurations such as a single droplet or a droplet array in a gas flow, the flow-droplet interaction has been investigated extensively on turbulence, evaporation and combustion modes [20–23]. Although simple configurations are useful to improve our understanding, actual turbulent flow fields in a spray are more complicated. Since a dense liquid spray contains many droplets and ligaments, whose size is comparable to the turbulence scale, and the liquid–gas relative velocity is high, it is expected that turbulence modulation will occur. Formation of wake and vortex shedding by droplets/ligaments will change the production and dissipation of the gas-phase turbulence. This phenomenon can alter flow structures and fuel/oxidizer mixing, and thus impact the combustion characteristics in the downstream dilute spray region. Therefore, it is important to investigate the turbulent mixing of the gas phase with finite-size droplets in a fuel spray to properly model spray dynamics and combustion.

In this study, to elucidate the turbulent mixing characteristics in the dense spray region, the DNS dataset of the primary atomization of a liquid fuel jet is utilized. Since the droplet distribution is non-uniform due to atomization [3,4], the turbulence and mixing characteristics in regions with distinct droplet number densities are investigated. To the best of our knowledge, this is the first study on turbulence and scalar mixing in a dense fuel spray.

2. DNS of an evaporating and atomizing fuel spray [6]

The liquid fuel *n*-heptane is injected from a round nozzle of diameter $D_N = 0.1$ mm into hot quiescent air (900 K, 30 atm) at a high speed (100 m/s). The bulk liquid Weber number ($We = \rho_l U_l^2 a/\sigma$) is 14,100 and the bulk liquid Reynolds number ($Re = \rho_l U_l a/\mu_l$) is 1477, where $a = D_N/2$, ρ denotes density, U the injection velocity, σ the surface tension coefficient, μ viscosity and the subscript l denotes liquid. Slip velocity still exists between the liquid and gas phases, with the estimation of the Stokes number around 20 ($St = \rho_l D_{32}^2 U_s/18\mu_g L$, where D_{32} is the Sauter mean droplet diameter, U_s the slip velocity, L the characteristic flow length and the subscript g stands for gas) [6]. The droplet size is $D_{32}/\eta = 4.3$, where η is the Kolmogorov scale.

The governing equations for mass, velocity, temperature, interface shape and species mass fractions of C_7H_{16}, O_2, CO_2, H_2O, and N_2 are solved [6]. The global one-step reaction model by Westbrook is used [6]. The reaction heat release