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Evolution of flame kernel in one eddy turnover of high-speed droplet laden shear layers

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ABSTRACT

A high-speed droplet-laden reacting shear layer is modeled numerically to analyze the dynamics of flame kernel for better understanding ignition and extinction processes in spray combustion. The droplet-laden shear layer, separating a hot-air stream from a monodisperse spray-laden air stream, is modeled by the Eulerian-Lagrangian approach, in which the continuous phase is governed by the compressible Navier-Stokes equations together with species transport equations and the discrete droplets are tracked by the Lagrangian method. The convective flux terms of the conservative equations are solved by an adaptive central-upwind WENO scheme. Two-way coupling interactions consider exchanges of mass, momentum, and energy between the carrier-gas fluid and the liquid-fuel spray. The shear layer convective Mach number is specified as 0.4 in the present study, and hence, large scales of motion dominate both the fluid mixing and the droplet dispersion. The preferential concentration of droplets is observed. Auto-ignition kernels occur in the high-strain regions where sufficient fuel vapors distribute near the hot stream-boundary. The incipient chemical reaction consumes the available fuel vapors through a diffusion flame combined with a thin premixed flame, as a lean deflagration propagates across the mixing layer towards the spray. The present results unveil two different types of extinction behavior depending on the local strain rate and the available fuel for the reaction kernel. The latter type of extinction originates when the separated flame kernel is entrained into the core of an adjacent vortex but droplets cannot be entrained in the eddies to produce gaseous fuels for the chemical reaction due to the preferential segregation effect. The dynamics of ignition and extinction in the shear flows depend on the droplet dispersion, the droplet evaporation rate and the diffusion of fuel vapor.

1. Introduction

Ignition and extinction of a flammable mixture are fundamental problems in combustion science and prevention of industrial explosions. Compared with abundant knowledge available on ignition and extinction in non-premixed gaseous combustion, the dynamics of ignition and extinction in dispersed fuel sprays are still not thoroughly understood, as recently reviewed by researchers (Li, 1997; Sirignano, 2010; Mastorakos, 2009; Wandel, 2013; Borghesi and Mastorakos, 2016), who have pointed out that a series of key problems, such as modeling of atomization and sprays, auto-ignition and spark ignition in turbulent non-premixed flames and combustion instability, are required for further investigation.

Due to the key role of ignition and extinction in numerous technological applications, the vaporization and combustion of fuel sprays has been the purpose of many modeling efforts since their fundamental role in numerous technological applications (Faeth, 1983; Sirignano, 1983; Aggarwal, 1998; Chiu, 2000; Jenny et al., 2012). Direct numerical simulations (DNS) and large eddy simulations (LES) of multiphase combustion (Miller and Bellan, 1999; Reveillon and Vervisch, 2005; Almeida and Jaberi, 2006; Wang and Rutland, 2007; Neophytou et al., 2012) are hindered by many complicating factors, such as atomization, evaporation mechanism of group droplets, spray flame structures and droplet-turbulence-

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combustion interactions, since such above complex phenomena contain a series of disparate time and length scales associated with the chemistry and multiphase fluid turbulence.

In typical liquid-fueled combustors, the atomized liquid fuel droplets are heated up by the surrounding gas or the co-flow with high temperature, the evaporation of which thus relies on the amount of heat transferred from the ambient gas. On the other hand, the heat exchange between the liquid and gas phases could be enhanced by droplet dispersion induced by the local turbulence. Therefore, auto-ignition will occur if a suitable mixing in molecular level is achieved and the temperature of mixture elements is considerable. Since in most applications the fuel-injection velocities are larger than the premixed-mixture burning velocity, combustion stabilization pertains to auto-ignition of the fuel-oxygen mixture and further anchoring flame. However, the local accumulation of fuel vapors evaporated by the preferential segregation of fuel droplets could result in thermal runaway and explosion. Extinction usually turns out in the high-strain regions and sometimes is induced by the cooling from the latent heat of evaporation. Therefore, stable combustion as well as ignition prevention are controlled by the complex interaction of turbulent transport, droplet heating and vaporization, and gas-phase chemical reactions.

Investigations of laminar shear layer configurations have been found to be instrumental in understanding of turbulent combustion (Mastorakos, 2009). Furthermore, in practical applications, the multiphase reacting flow is highly turbulent and the consideration of shear turbulence helps to explore the physics in a more reliable and real configuration, as shown in Fig. 1. The turbulent shear layer flow is involved a stream of hot air and a stream of cold air laden with monodisperse spray droplets. The figure also depicts the transport of droplets in the presence of turbulence motion.

As known, the parameter, called as particle Stokes number (St), generally determines the dispersion characteristics of droplets in turbulent flows (Balachandar and Eaton, 2010),

$$\mathrm{St} = \frac{\tau_\mathrm{d}}{\tau_\mathrm{f}} \tag{1}$$

where τ_d describes the characteristic acceleration time of the droplets and τ_f is the integral time scale characterizing the dynamics of the large vortices. Different values of St are associated with different behaviors of droplet dispersion. For St≪1, the particles/droplets behave as flow tracers and are entrained inside the large scale turbulent eddies. For example, fumes from combustion, sublimation or distillation show good momentum response behavior in the air eddies. A particular interaction of the droplets with the local turbulent vortices occurs as the Stokes number increases to $\mathrm{St} = O(1)$ and droplets are ejected from the spray stream through the high-strain vortex-braid regions, resulting in non-uniform droplet distributions (as seen Fig. 1). The droplets preferentially accumulate in the high-strain low-vorticity regions and it is the phenomenon of preferential concentration. Numerical (Squires and Eaton, 1991) and experimental (Longmire and Eaton, 1992) evidence for these so-called preferential-concentration phenomena of inertial particles has been reported. A more detailed scenario is depicted in Fig. 2. Large scale eddies formed in the shear layer entrain the hot air (red arrow) and the cold air (blue arrow) from two co-flow streams. Hence, the two fluids with different temperature meet with each other and mix in the vortices. The droplets traverse the shear layer associated with the entrainment of the cold air and vaporize in high-strain vortex-braid regions surrounded by hot air. The fuel vapor generated by droplet evaporation mixes with the surrounding air to form reactive pockets that flow downstream. If the fuel vapor concentration in these reactive pockets is sufficiently high for the fuel-oxidizer mixture to be flammable, auto-ignition occurs downstream. For St≫1, the droplets on the spray side of the shear layer have large inertia and are insensitive to the velocity perturbations induced by the large vortices motion and hence continue moving along their initial trajectories. Thus, the droplets are surrounded by the cold carrier gas, thereby hindering droplet vaporization and ignition.

The effects of the large eddies associated with the integral scales of the turbulent shear layer on the dispersion of the droplets are discussed above. The motions of eddies and their shearing have an influence on the fuel-oxidizer mixing and ignition. The shear layer contains eddies having a series of length scales. Large eddies coexist and interact with smaller eddies. Although these smaller turbulent eddies could also affect mixing and reaction, their effect on ignition is less prominent than that of the large vortices. In addition, the spray ignition characteristics in laminar shear layers for St≪1 have been well investigated (Martínez-Ruiz et al., 2013) by a two-continua formulation. Therefore, the present research is focused on the dynamics of ignition and extinction of liquid fuel droplets with $\mathrm{St} = O(1)$ in large scale turbulent eddies by means of two-dimensional DNS. A Eulerian-Lagrangian formulation will be applied to solve the supersonic multiphase shear-layer flows (Ren et al., 2015; Wang et al., 2016). The gas-phase conservation equations, which include source terms associated with the counteracting force and the heating and vaporization from the droplets, combine a one-step Arrhenius model adopted for the chemical reaction. A Lagrangian description of individual droplets is employed to study the motion and vaporization of liquid phase.

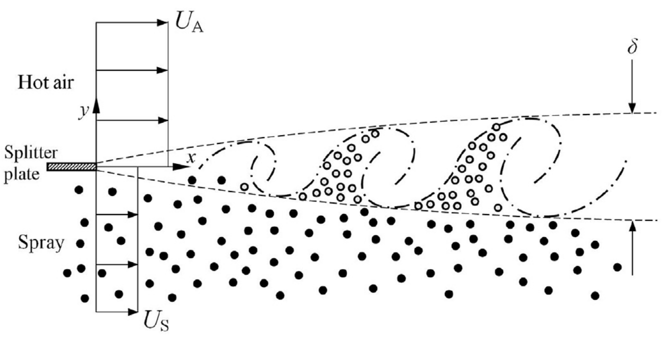

Fig. 1. Schematic of a fuel spray in a two-dimensional turbulent shear layer. Here, the black dots indicate fuel droplets, with light grey droplets corresponding to vaporizing droplets. The dashed lines represent the edges of the shear layer. The dash-dot lines represent the scales of large scale vortices.

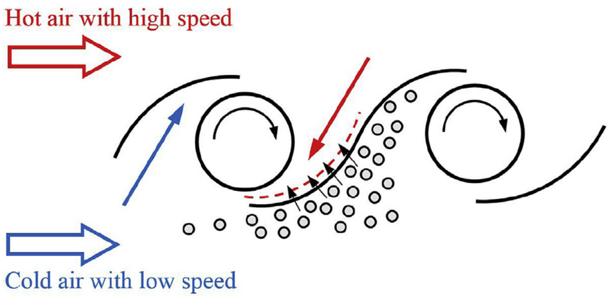

Fig. 2. Schematic of large turbulent eddies entraining the air and the fuel spray. Igniting regions are sketched with red dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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