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Effects of finite-rate droplet evaporation on the ignition and propagation of premixed spherical spray flame

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ABSTRACT

Droplet evaporation might have great impact on fundamental spray combustion processes such as ignition, flame propagation, and extinction. In this study, we adopt and analyze a simplified model for spherical spray flame initiation and propagation in an overall fuel-rich or fuel-lean pre-mixture containing fuel droplet with finite-rate evaporation, fuel vapor, and air. We consider the limit of small droplets such that the medium can be considered as a continuum and adopt the sectional approach to model poly-disperse spray. Moreover, the thermal-diffusive model with constant density is employed and the spherical flame is assumed to propagate in a quasi-steady state. Under these assumptions, analytical correlations describing the change of flame propagation speed with flame radius are derived for the premixed spherical spray flame. The initial droplet load, vaporization Damköhler number, Lewis number, and ignition power are included in these correlations. Based on these correlations, spherical spray flame initiation and propagation are investigated with the emphasis on assessing the impact of droplet evaporation at different Lewis numbers. It is found that the spray flame propagation speed, Markstein length, and minimum ignition power are affected in different ways by the initial droplet load and vaporization Damköhler number and that the influence depends on Lewis number. Moreover, the influence of droplet evaporation on the fuel-lean case is greatly different from that on the fuel-rich case. This is mainly due to the facts that the fuel-rich spherical spray flame is affected by droplet evaporation only through latent heat of vaporization absorbed in the pre-flame and post-flame zones; while the fuel-lean spherical spray flame is affected by droplet evaporation through (1) latent heat of vaporization absorbed in the pre-flame and post-flame zones and (2) change in local effective equivalence ratio. For hydrocarbon fuels with large Lewis number, the lean spray flame is much more difficult to be ignited compare to the equivalent purely gaseous flame.

1. Introduction

Relight during flight is one of the most important problems in jet-engine and it becomes even more critical in the oxygen/fuel deficiency and the presence of liquid fuel or water droplets. Droplet evaporation might have great impact on ignition and flame propagation processes. The realistic systems contain poly-disperse sprays and turbulent flows, for which investigation on spray flame initiation and propagation processes can be undertaken only by numerical simulation. Unfortunately, numerical simulation is usually limited to specific fuel and conditions, and hence the conclusions are lack of generality. To get a general understanding of spray combustion, here we conduct theoretical analysis on a deliberately simplified model for spherical spray flame initiation and propagation. Since the spark ignition process can be approximately modeled as spherical flame initiation and propagation, the spherical spray flame initiation and propagation can be used to assess the effects of droplet evaporation on fundamental spray combustion processes.

In the literature there are many studies on spray flame propagation. Continillo and Sirignano [1,2] first numerically examined the spherical flame propagation in a fuel spray mixture and found that multiple flames occur in spray combustion. Chiu and Lin [3] investigated the transient poly-disperse fuel droplet cluster combustion. Lin et al. [4,5] analyzed steady-state propagation of one-dimensional mono-disperse spray flames in off-stoichiometric mixtures. Kalma and coworkers [6,7] reported the time evolution

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Nomenclature

A	pre-factor of reaction
C	sectional vaporization coefficient
C_P	specific heat at constant pressure
D	Fick diffusion coefficient
Da	vaporization Damköhler number
E	evaporation-related integral (see Eq. (29))
F	gaseous fuel
f_i	amount of evaporation (i = 1, 2, 3)
H	Heaviside function
I_1, I_2	integral function (see Eq. (28))
K	flame stretch rate
L	Markstein length
l_0^{ad}	flame thickness of an adiabatic planar flame
Le	Lewis number
O	oxygen
Q	ignition power
q_c	reaction heat-release per unit mass of the deficient reactant
q_v	latent heat of vaporization
R^0	universal gas constant
R_f	flame radius
R_v	front of onset vaporization
S_{ad}^0	laminar flame speed of an adiabatic planar flame
T	temperature
T_{ad}^0	flame temperature of an adiabatic planar flame
T_v	reference temperature (close to the boiling temperature)
t, r	temporal and spatial coordinates
U	flame propagation speed
Z	Zel'dovich number

Greek letters

α	parameter used to distinguish the fuel rich (α=0) and fuel-lean (α=1) cases
δ	initial droplet load
η	moving coordinate attached to the propagating flame front
η_v	location of the front of onset vaporization in the moving coordinate
λ	heat conductivity of the mixture
ν	molar stoichiometric coefficient
ρ	density of the mixture
σ	thermal expansion ratio
ω_c	chemical reaction rate
ω_v	finite evaporation rate
ϖ	droplet-burning-related sink term (see Eq, (9))
Δ_M	thicknesses for mass diffusion
Δ_T	thicknesses for temperature diffusion

Superscripts

$\sim$	dimensional quantity
0	at zero stretch rate

Subscripts

c	critical quantity
d	corresponding to the liquid fuel (droplet)
F	corresponding to the gaseous fuel
f	at the flame front
O	corresponding to the oxygen
u	quantity in the fresh mixture
v	at the front of onset vaporization

of spherical propagating poly-disperse spray flames using the sectional approach [8]. Bradley et al. [9] experimentally assessed the mass burning velocities, entrainment velocities and flame instabilities of the aerosols using the propagating spherical flame. Greenberg and coworkers [8,10–17] systematically analyzed the propagation of planar and spherical spray flames using slowly varying flame (SVF) approach. Specifically, stoichiometry and poly-disperse effects were examined and a heterogeneous-dominated burning velocity formula were reported in [8,10]; the combined effects of heat loss induced by droplet evaporation and radiation on the extinction of fuel-rich spherical spray flame were addressed in [12]; the effects of finite-rate evaporation and droplet drag on fuel-rich flame propagation were assessed in [14]; the influence of stretch rate on poly-disperse spherical spray flames was investigated for the first time in [17]. In these studies, droplet evaporation was found to strongly affect flame propagation. However, highly stretched spray flames with small flame radius were not considered in these studies and thereby the ignition kernel development after spark was not investigated. To the authors' knowledge, in the literature there are few theoretical studies on the ignition of spray flames especially for the fuel-lean case. Therefore, spray flame initiation for both fuel-rich and fuel-lean cases will be explored in this study.

Lefebvre and coworkers [18–20] conducted a series of experimental and numerical studies on spark ignition of heterogeneous mixtures. When a kerosene-air mixture was ignited by spark, the minimum ignition power was found to be affected by fuel volatility and initial droplet load. Ballal and Lefebvre [19] showed that under certain conditions the spray flame initiation process is vaporization-dominated rather than kinetically-dominated. Aggarwal and coworkers [21–23] numerically studied the effects of the initial droplet size, equivalence ratio, and fuel volatility on spray flames. A comprehensive review of previous numerical studies on spray ignition phenomena was conducted by Aggarwal [24]. More recently, Neophytou and Mastorakos [25] have numerically studied one-dimensional planar flame propagation in sprays of n-heptane and n-decane with detailed chemistry and transport. It is found that the maximum speed is achieved with small droplet diameter and long residence time under fuel-lean conditions. Neophytou [26] gave a literature review on ignition and flame propagation in sprays and conducted direct numerical simulations of combustion in laminar and turbulent sprays. Though many numerical studies were conducted in the literature, the effects of initial droplet load, finite-rate evaporation, and Lewis number on spray flame initiation are still not well understood.

The present work aims to develop a simplified theoretical description of spherical spray flame initiation and propagation and to assess the effects of droplet evaporation for both fuel-rich and fuel-lean cases. The focus is on examining how the spherical flame propagation speed, Markstein length, and minimum ignition power are affected by the initial droplet load and vaporization Damköhler number at different Lewis numbers. It is noted that many assumptions are made in theoretical analysis and thereby qualitative instead of quantitative information can be provided. Nevertheless, the theoretical analysis on ignition and propagation of spray flames will be helpful to understand the underlying mechanisms and to give physical insight into the relight problem.

The rest of the paper is organized as follows. The mathematical model and analytical solution are introduced in the next section. In Section 3, the propagating spherical spray flame without and with ignition power deposition at the center are analyzed for both