

Observations of soot during droplet combustion at low gravity: heptane and heptane/monochloroalkane mixtures

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Abstract—Experimental observations of the combustion of sooting fuel droplets, performed in a drop tower to create a low gravity environment, are reported. Free *n*-heptane droplets and suspended droplets of heptane, monochloroalkanes, and mixtures of monochloro-octane and heptane were studied. Initial droplet diameters ranged from 0.4 to 1.1 mm. The results suggest that soot may influence droplet vaporization rates. Spherical symmetry of the flame allowed for extended observation of soot agglomerates inside the droplet flame. Effects of slight convective flows were also observed, both through variations of natural convection around the suspended droplets and through variations in the drift velocities of the unsupported droplets. Slight convective flows around the suspended droplets reduced flame luminosity as well as soot accumulation inside the flame and increased droplet vaporization rates. Mixing monochloro-octane with *n*-heptane demonstrated the effectiveness of *n*-heptane in reducing soot emissions from the flames of the chlorinated fuels. Finally, trends of initial droplet diameter with burning rate were observed and may be linked to the effect of droplet size upon soot formation inside the flame.

1. INTRODUCTION

ALTHOUGH analytical models provide significant insight into the physical processes of droplet combustion, their ability to accurately predict experimentally observable quantities such as burning rates and flame diameters is currently limited to fuels which have non-sooting flames. The presence of soot in the gas surrounding the droplet may alter the heat and mass transfer between the droplet and its flame, which in turn controls the burning rate and propensity for flame extinction. Current theories of droplet combustion do not account for the influence of soot. Recent experimental results of free/unsupported droplets burning in near spherically symmetric environments have underscored the potential importance of soot in droplet combustion [1–3]. Differences in the means of ignition, in convective flows around the droplets due to the various droplet deployment methods, or even in initial droplet diameters may have been responsible for reported differences in the experimental results by their effect on soot dynamics. In particular, the influence of initial droplet diameter may be noteworthy and is not addressed in the classical quasi-steady theory of droplet combustion [4]. The recent experimental results point to initial droplet diameter as affecting the extent of soot accumulation inside the droplet flame as well as the burning rate.

The present study was undertaken to further docu-

ment the potential influence of soot on droplet burning characteristics. Qualitative influences of initial droplet diameter, fuel composition, and slight convective gas flows around the droplet on soot formation and accumulation were examined. The present experiments were performed in a near buoyancy-free (low gravity) environment with the droplets being nearly stationary in order to promote spherically symmetric burning. The near spherically symmetric environment also allows for greater sensitivity of parametric influences on soot formation because natural or forced convection does not rapidly sweep the soot through the flame. This experimental study was carried out in the hope of providing information for future improvements of droplet combustion models.

n-Heptane was selected as a test fuel for comparison with the extensive previous heptane droplet combustion studies at low gravity. Heptane droplets were also studied to assess the influence of recent experimental modifications on the burning process. Monochlorinated alkanes were studied because of their importance in the incineration of hazardous waste liquids. Finally, mixture droplets of *n*-heptane and monochloro-octane were burned in order to assess the influence of fuel composition upon sooting where both fuel mixture components are prone to form soot—although heptane significantly less so than monochloro-octane.

The experimental method employed both free-floating (i.e. unsupported) and fiber-supported droplets. The two means of droplet deployment yielded a two-fold range of initial droplet diameters—around 0.5 mm for the unsupported droplets and 1 mm for fiber-supported droplets. This range resulted in observable

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NOMENCLATURE

C_m	momentum exchange coefficient (= 1.14 in model)	V	radial diffusion velocity in gas phase
C_p	specific heat capacity in the gas phase	v	velocity
C_s	thermal slip coefficient (= 1.17 in model)	W_i	molecular weight of species i
C_t	kinetic theory coefficient for temperature jump at interface (= 2.18 in model)	Y_i	mass fraction of species i .
D	mass diffusion coefficient of fuel in the gas phase	Greek symbols	
d	droplet diameter	β	thermal expansion coefficient
F'_D	dimensional Millikan drag force in the radial direction on stationary particle	ζ	net force on particle in the radial direction
F_D	non-dimensional drag force in the radial direction on stationary particle	λ	mean free path
F_{TH}	non-dimensional thermophoretic force in the radial direction	μ	dynamic viscosity
g	acceleration due to gravity level	ξ	dimensionless position inside the droplet flame
Gr	Grashof number	ρ	density
K	vaporization rate of droplet	τ	non-dimensional time.
R	universal gas constant	Subscripts	
Re	Reynolds number	d	droplet surface
r	radius	F	fuel
T	temperature	f	flame position
t_F	average residence time for fuel molecules in the gas phase	g	gas phase
U	non-dimensional momentum of particle in the radial direction	l	liquid phase
		p	soot particle
		∞	far ambient.

differences in burning rates and extents of sooting of *n*-heptane droplets which were attributed to initial diameter effects. The larger droplets experienced slight axial vapor flows in the latter period of combustion due to natural convection induced by an increase in air drag on the experimental package during free fall. This provided an opportunity to study the evolution of the droplet flame and soot structure caused by small axial vapor flows around the droplet.

2. EXPERIMENTAL DESCRIPTION

2.1. Experimental technique and conditions

Burning of both free unsupported droplets and droplets suspended from a small quartz fiber was observed. Free droplets were preferred because a suspension fiber may have disrupted soot structures above the droplet and influenced the potential for flame extinction or for microexplosion which can arise from internal boiling due to nucleation at the fiber surface. However, safety considerations encouraged the use of suspended droplets for the monochloroalkanes, because the suspended droplet method required less exposed fuel for the experimental set-up. Furthermore, the difficulty of obtaining perfectly stationary free droplets led to burning suspended droplets in the present study, but no data were taken near the end of burning when the droplets became too small.

Experiments were conducted in a drop tower facility, which has been described in detail elsewhere [3, 5, 6], to create a low-gravity ambience for droplet combustion. The drop tower provided 1.2 s of free fall. The experimental observation time was long enough to record the complete burning of the small free droplets studied and about 75% of the projected burning history of the larger supported droplets. The experimental drop package included the combustion chamber, ignition transformers, a high-speed movie camera, and a CCD video camera. Ambient conditions in the combustion chamber were 0.101 MPa and $25 \pm 2^\circ\text{C}$.

Free unsupported droplets of *n*-heptane were produced by a droplet generator based upon the ink jet method. A droplet was captured in a relatively stationary configuration by shooting it vertically upward and releasing the experimental package into free fall as the droplet reached its apex. Droplets generated by this method had initial diameters ranging from 0.4 to 0.5 mm. Modifications of the free droplet experiment [6, 7] from previously reported experiments [3, 5] included ignition during free fall, subsequent removal of the electrodes from the vicinity of the burning droplet, and better control of the ambient gas composition around the droplet with a more open droplet generator design and thorough flushing of the combustion chamber before the experiment.

For monochloroalkane fuels and chloroalkane/

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