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Droplet combustion in the presence of acoustic excitation

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ABSTRACT

This experimental study focused on droplet combustion characteristics for various liquid fuels during exposure to external acoustical perturbations generated within an acoustic waveguide. The alternative liquid fuels include alcohols, aviation fuel (JP-8), and liquid synthetic fuel derived via the Fischer–Tropsch process. The study examined combustion during excitation conditions in which the droplet was situated in the vicinity of a pressure node (PN). In response to such acoustic excitation, the flame surrounding the droplet was observed to be deflected, on average, with an orientation depending on the droplet's relative position with respect to the PN. Flame orientation was always found to be consistent with the sign of a theoretical bulk acoustic acceleration, analogous to a gravitational acceleration, acting on the burning system. Yet experimentally measured acoustic accelerations based on mean flame deflection differed quantitatively from that predicted by the theory. Phase-locked OH^* chemiluminescence imaging revealed temporal oscillations in flame standoff distance from the droplet as well as chemiluminescent intensity; these oscillations were especially pronounced when the droplets were situated close to the PN. Simultaneous imaging and pressure measurements enabled quantification of combustion-acoustic coupling via the Rayleigh index, and hence a more detailed understanding of dynamical phenomena associated with acoustically coupled condensed phase combustion processes.

1. Introduction and background

The fundamental character of a single isolated burning fuel droplet represents a heterogeneous reactive process whose behavior has been explored extensively. The droplet evaporates and acts as a source of fuel vapor which reacts with an oxidizer to form a flame front surrounding the droplet. The fuel droplet is also commonly used as a fundamental model for condensed-phase combustion processes. Classical studies have shown the d^2-law to be applicable to essentially spherical burning droplets in a microgravity environment [1], and to be approximately valid for burning droplets in a gravitational environment, even under non-quiescent conditions [2,3]. The standard d^2-law [4,5] is represented by:

$$d^2(t) = d^2(t=0) - Kt, \qquad (1)$$

where d is the (spherical) droplet diameter, K is the burning rate constant, with typical units of mm^2/s, and t is time. In normal gravity conditions, a suspended burning droplet cannot maintain a spherical geometry due to gravitational and surface tension forces; the former effect is virtually eliminated, of course, in microgravity experiments. In order to determine K using Eq. (1), an effective diameter for the non-spherical droplet is often determined by equating the experimentally estimated volume of the actual droplet to the volume of an equivalent spherical droplet of diameter d_{eqvs} [6] and then using d_{eqvs} in Eq. (1).

In recent years a few studies have examined fuel droplets burning in an acoustically resonant environment within an acoustic waveguide. Several experimental studies have shown that there can be a moderate to significant increase in fundamental heat and mass transfer rates from burning droplets with the imposition of an external acoustical field [2,7–9], similar to augmentation of transport processes in other reactive environments such as gas turbine combustion chambers. Experiments by Blaszczyk [2] suggest a frequency-dependent increase in burning rate constant during exposure of a burning droplet to acoustic excitation in normal gravity. Saito et al. [8,9] examine the effects of acoustic waves on single evaporating and burning kerosene droplets, finding that when a standing acoustic wave is created and the fuel droplet is situated at a pressure node, PN (or velocity antinode VAN), there can be a two to threefold increase in evaporative or combustion rate constants, while if the droplet is located at a pressure antinode (PAN) or velocity node (VN), there is little appreciable change in the evaporation or combustion rates.

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Some experiments have involved acoustical excitation of burning droplets in microgravity, where the absence of natural convection arising from gravitational forces allows a degree of isolation of the effects of acoustic excitation [10–12]. Okai et al. [11] observe in microgravity that the burning rate constant is nearly proportional to the product of frequency and square of the displacement amplitude of the acoustic disturbance. The microgravity experiments of Tanabe et al. [10,12,13], involving a burning *n*-decane droplet situated at the PN or between the PN and PAN of a standing wave in a closed duct, show significant increases in the burning rate constant as the maximum velocity perturbation is increased, as high as 85% over the unforced value of the burning rate constant.

Methanol droplet combustion studies in microgravity and normal gravity by our group [14,15] focus on combustion characteristics during exposure to standing acoustic waves within a waveguide. For pressure excitation amplitudes within the waveguide exceeding about 135 dB, droplet burning rates in microgravity are seen to increase by over 75% and 200% for droplets situated in the vicinity of PAN and PN locations, respectively. In contrast, in normal gravity, droplets situated near a pressure node produce only very moderate increases in burning rate, about 11–15% higher (at 138 dB forcing) than for non-acoustically excited, burning droplets, and produce no significant change in burning rate when the droplet is situated near the PAN.

In both microgravity and normal gravity experiments in Dattarajan et al. [14], orientation of the flame enveloping the droplet depends on the droplet's position within the waveguide. In the vicinity of a PN, the flame is oriented systematically away from the PN; for instance, when the droplet is shifted to the right of a PN, its flame appears deflected to the right. This type of bulk alteration in flame orientation with droplet position is also observed in microgravity droplet combustion experiments by Tanabe et al. via visualization of the sooting flame's wake [10,12,13]. Such flame deflections are interpreted by Tanabe et al. in terms of the magnitude and orientation of an acoustic radiation force F_a acting on the "sphere" of hot gases nominally surrounding the burning droplet, similar to acoustic radiation forces acting on a solid sphere or particle [16–18]. This acoustic radiation force relevant to a sphere containing hot gases is represented by

$$F_a = \alpha\left(\rho_p - \rho_o\right)\mathcal{V}\frac{\partial(\overline{u'^2})}{\partial x} = \left(\rho_p - \rho_o\right)\mathcal{V}g_a \qquad (2)$$

Here ρ_p is the density of the hot combustion products and other gases within the sphere, ρ_o is the density of ambient air external to the flame, $\mathcal{V}$ is the volume of the sphere containing the hot gases, and x is the distance of the droplet measured from the waveguide center, where the PN or PAN is located. $\overline{u'^2}$ is the mean of the square of the amplitude of the local perturbation velocity, u', within the waveguide at location x. The coefficient α is dependent on gas densities, and takes the form

$$\alpha \equiv \frac{3\rho_o}{2\left(2\rho_p + \rho_o\right)}. \qquad (3)$$

The term g_a in Eq. (2) represents an "acoustic acceleration", analogous to gravitational acceleration, where $g_a \equiv \alpha\frac{\partial\overline{u'^2}}{\partial x}$. Hence the acoustic radiation force F_a has the same form as a buoyancy force F_b acting on a light object of density ρ_p and volume $\mathcal{V}$, surrounded by a heavier fluid of density ρ_o in a gravitational field with acceleration g_o, i.e., $F_b = \left(\rho_p - \rho_o\right)\mathcal{V}g_o$. This leads Tanabe et al. [10,12,13] to suggest that the acoustic radiation force's influence on droplet combustion and flame deformation is similar to that of a gravitational force.

As with the burning droplets observed in Dattarajan et al. [14], the burning droplets in microgravity in Tanabe et al. [10,12,13] have flames oriented away from the PN when situated on either side of the PN, thus with a bulk "flow" deflecting the flame away from the PN or toward the PAN. Tanabe et al. also studied premixed flames [19] as well as a single hot wire [13] in the vicinity of pressure nodes and antinodes in microgravity. Asymmetries in the flame or heated flow region again appear to be qualitatively consistent with the notion of an acoustic radiation force acting on the hot gases and/or a flame as expressed in Eq. (2), with increasing asymmetry arising with an increase in acoustic excitation amplitude. Yet there has been no quantitative validation of the x-dependence of the acoustic radiation force model in Eq. (2), other than to correlate increases in transport properties, e.g., the burning rate constant K for a droplet, with increases in the acoustic acceleration g_a [10]. While Dattarajan et al. [14] observe the same qualitative confirmation of Eq. (2) in terms of flame orientation, there is no quantitative verification of the equation in that study, either. In fact, in contrast to the theoretical prediction in Eq. (2) and an image presented in Tanabe et al. of a more symmetric, unperturbed flame, when the droplet is situated precisely at a PN in Dattarajan et al. [14], significant flame oscillation and relative instability in the direction of deflection are observed, thus making it difficult to even quantify burning rates.

The present studies build on these earlier methanol droplet combustion experiments in microgravity and normal gravity [14,15] in an attempt to examine Eq. (2) from a quantitative perspective and in relation to acoustically coupled combustion processes. A range of alternative fuels, including alcohols (ethanol and methanol), aviation fuel (JP-8), and liquid synthetic fuel derived from natural gas via the Fischer–Tropsch process, (called "FT" fuel) were examined. A 50–50 blend of JP-8 and FT fuel has undergone extensive evaluation at the Air Force Research Laboratory as an alternative aviation fuel and has been certified for operation of the entire Air Force fleet [20].

2. Experimental facility and methods

2.1. Acoustic waveguide and pressure measurements

In the present experiments, standing acoustic waves were generated in a closed cylindrical waveguide by two loudspeakers, one placed at each end. The waveguide was filled with air at atmospheric pressure and room temperature. The applied frequency f_a was sufficiently low that only planar (one-dimensional) waves propagated in the waveguide. Sinusoidal forcing signals were applied to each loudspeaker via a National Instruments USB-6251 data acquisition board (DAQ) controlled using LabVIEW™. A stereo amplifier, serving as an intermediary between the DAQ and the loudspeakers, administered a constant voltage gain to the forcing signals. The speakers were connected to the amplifier so as to impart a half period phase difference ($\Delta\phi = 180^\circ$) between individual forcing signals, hence the speaker pair functioned out-of-phase to enable the desired standing waves (see below). Prior experiments by Dattarajan [14,15] and later by Rodriguez [21] used a speaker and planar reflector rather than two speakers bounding the waveguide. The results reported here involved an arrangement of two speakers to enable greater symmetry in the waveguide. More extensive laboratory-based speaker–reflector results and comparison to the speaker–speaker arrangement may be found in [21,22], respectively.

A detailed schematic diagram of the experimental apparatus is shown in Fig. 1. The waveguide was constructed of aluminum, with an inner diameter of 11.4 cm and a maximum length of 90 cm. Quartz windows were situated at either side of the center of the waveguide to provide optical access. Woofer type 8-Ω loudspeakers with a maximum power output of 35 W were placed at either end of the waveguide. A rod assembly connecting the two speakers