FUEL DROPLET COMBUSTION IN THE PRESENCE OF ACOUSTIC EXCITATION

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Summary This experimental study focuses on fuel droplet combustion during exposure to acoustical excitation within a one-dimensional waveguide. During such exposure, the flame surrounding the burning droplet is observed to be deflected, on average, with an orientation dependent on the droplet's relative position with respect to the pressure node (PN). While average flame characteristics are consistent qualitatively with the sign of a theoretical acoustic acceleration, which is analogous to gravitational acceleration, the experimentally measured acoustic acceleration based on flame deflection differs quantitatively from that predicted by theory. Phase-locked OH* chemiluminescence imaging reveals temporal oscillations in flame position and standoff distance from the droplet surface during acoustic excitation, resulting in oscillatory heat release whose magnitude is dependent on the relative droplet position in the waveguide. These results suggest an explanation for the discrepancy between theory and experiments, as well as a phenomenological mechanism by which the Rayleigh criterion amplifies unstable combustion processes.

BACKGROUND AND CONTEXT OF PRESENT STUDIES

The fundamental character of a single isolated burning fuel droplet represents a heterogeneous reactive process whose behavior has been explored over many years. Here the droplet evaporates and acts as a source of fuel vapour that reacts with air to form a flame front surrounding the droplet. In recent years a number of research groups have examined fuel droplets burning in an acoustically resonant environment within an acoustic waveguide. Several experimental studies, for example[1,2], have shown that there can be a moderate to significant increase in heat and mass transfer rates from burning droplets with the imposition of an external acoustical field, similar to augmentation of transport processes during acoustic coupling in other reactive environments such as gas turbine or liquid rocket engine combustion chambers. Acoustical excitation of burning droplets in microgravity, with the absence of natural convection arising from gravitational forces, allows isolation of the effects of acoustic coupling to the combustion process[3,4,5]. For example, methanol droplet combustion studies in microgravity by our group[5] demonstrate that burning rates can increase by over 75% and 200% for droplets situated in the vicinity of pressure antinodes and pressure nodes of standing acoustic waves, respectively, in a waveguide. In normal gravity, however, droplets situated near a pressure node produce only moderate increases in burning rate, about 11-15% higher than for non-acoustically excited, burning droplets, and produce no significant change in burning rate when the droplet is situated near the pressure antinode.

In both microgravity and normal gravity, burning droplets situated in the presence of standing acoustic waves are observed to experience a bulk flame deflection away from the pressure node and toward the pressure antinode. Hence the flame enveloping the droplet has a different orientation when the droplet is situated on one side of the pressure node as compared with positioning on the opposite side. Such flame deflections are interpreted by Tanabe, et al.[3,4] in terms of the magnitude and orientation of an acoustic radiation force acting on the "sphere" of hot gases nominally surrounding the burning droplet. The mathematical form of the proposed acoustic radiation force F_R has the same form as a buoyancy force F_B acting on a light object of density ρ_s and volume V, surrounded by a heavier fluid of density ρ_o in a gravitational field with acceleration g_o, i.e., $F_B = (\rho_s - \rho_o) V g_o$. This leads Tanabe, et al. to suggest that the influence of an acoustic acceleration g_a on droplet combustion and flame deformation is similar to that of gravitational acceleration. Flame orientation studies in microgravity[3,4,5] show qualitative consistency with the notion of an acoustic acceleration.

Quantitative evaluation of the acoustic acceleration for fuel droplet combustion has been undertaken in recent studies by our group[6], using the flame orientation angle measured from visible images to determine an experimental estimate of g_a. The aim of the present studies is to continue to quantify bulk flame behavior as well as flame motions throughout the acoustic cycle as a means of explaining discrepancies between theory and experiments and enhancing our understanding of fundamental combustion-acoustic coupling.

EXPERIMENTAL APPROACH AND SAMPLE RESULTS

The present experiments explore a range of alternative liquid fuel droplets (ethanol, methanol, liquid synthetic fuel derived from coal via the Fischer-Tropsch process, aviation fuel JP-8, and a 50-50 blend of the FT synfuel and JP-8) created and undergoing sustained combustion in a one-dimensional acoustic waveguide bounded by two speakers. The droplet's position within the waveguide is fixed, with constant delivery of fuel to the droplet through a glass capillary via a syringe pump. The relative position of the droplet within the waveguide is altered by moving the pair of speakers relative to the droplet while maintaining a fixed waveguide length and standing wave conditions, as done in

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prior experiments[5,6]. Flame visualization is accomplished here via phase-locked UV imaging with a Nanostar intensified CCD camera, enabling quantification of OH* chemiluminescence and thus the temporally evolving reaction zone. Flame deflection for droplets situated at various locations relative to a pressure node may be quantified from images shown, for example, in **Figure 1**. Consistent with the theory of Tanabe, et al.[3,4], flames are deflected away

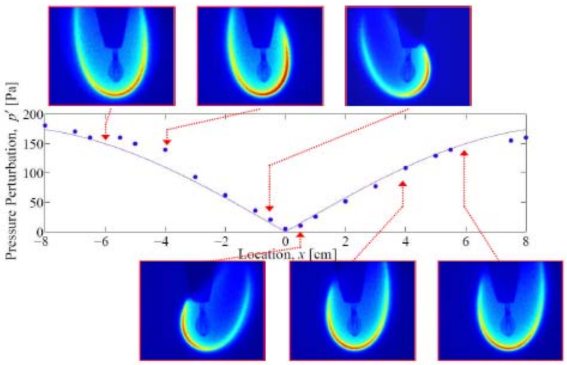

Figure 1. OH* chemiluminescence imaging of ethanol droplet combustion under the influence of acoustic excitation, for droplets positioned at various locations x on either side of the pressure node associated with a standing wave. Also shown are local measurements of the amplitude of pressure perturbations as compared with theory.

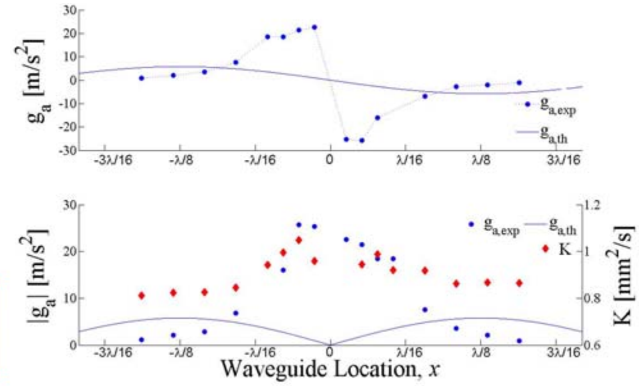

Figure 2. Upper plot: estimated experimental and theoretical acoustic accelerations g_a; lower plot: amplitude of theoretical and experimental g_a and average burning rate constant K. Data sets are plotted as a function of waveguide location for the ethanol droplet burning in the vicinity of a pressure node at an excitation frequency of 898 Hz.

from the pressure node (PN), with a flame "switch"' occurring near the PN. Yet the degree of flame deflection is visibly greater when the droplet is situated closer to the PN than further away; this contrasts the quantitative prediction from the theory of Tanabe, et al. As an example, the measured acoustic acceleration g_a associated with flame deflection differs quantitatively from theory, as indicated in the upper plot in **Figure 2**, even though the signs of g_a are consistent between theory and experiments. The magnitude of the experimentally measured acoustic acceleration g_a does appear to correlate with the droplet burning rate constant K for various locations within the waveguide, however, as indicated in the lower plot in **Figure 2**.

Phase-locked OH* chemiluminescence imaging of the flame zone allows temporally resolved exploration of this discrepancy between theory and experimental observations. Flame front position or standoff distance δ_f relative to the droplet surface may be quantified as a function of acoustic phase ϕ_p occurring over multiple acoustic cycles via OH* imaging. During reasonably high amplitude acoustic forcing, the entire flame appears to maintain a constant global shape while oscillating horizontally in a sinusoidal manner within the waveguide, changing position relative to the fixed droplet. Oscillations in δ_f as a function of ϕ_p show that lower frequency acoustic forcing (e.g., at a frequency of 332 Hz) appears to produce larger amplitudes of oscillation in flame standoff distance δ_f than at higher frequencies. There is also a dependence of mean flame standoff distance on fuel type, especially at higher frequencies where the flame does not respond as extensively over time to the applied excitation. In all cases these phase-locked results clearly demonstrate that the mean flame standoff distance becomes smaller and the amplitude of oscillation becomes larger as the droplet is situated closer to the PN; the latter is especially true for lower frequency acoustic excitation (332 Hz) as compared with higher frequency excitation at 898 and 1500 Hz. These findings are consistent with increases in burning rate constant in the vicinity of the PN, as indicated in **Figure 2**. The mechanism by which this increase in flame response occurs near the PN may be explored in the present studies via the Rayleigh criterion, whereby an acoustically coupled combustion instability is locally amplified if the non-steady heat release and pressure oscillations are in phase, while the instability is damped if the heat release and pressure oscillations are out of phase. The spatially dependent Rayleigh index helps to explain enhanced coupling between combustion and acoustics in this configuration.

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