Combustion and Flame 189 (2018) 46–61

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Periodic partial extinction in acoustically coupled fuel droplet combustion

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ARTICLE INFO

Article history:
Received 23 January 2017
Revised 21 March 2017
Accepted 14 October 2017

Keywords:
Acoustically-coupled combustion
Droplet combustion
Periodic partial extinction and reignition

ABSTRACT

This experimental study explored the response of burning liquid fuel droplets to one-dimensional acoustic standing waves created within a closed, atmospheric waveguide. Building upon prior droplet combustion studies quantifying mean and temporal flame response of several alternative fuels to moderate acoustic excitation (Sevilla-Esparza et al., 2014), the present work focused on higher amplitude acoustic forcing observed to create periodic partial extinction and reignition (PPER) of flames enveloping the droplet. Detailed examination of ethanol droplets exposed to a range of acoustic forcing conditions (frequencies and amplitudes in the vicinity of a pressure node) yielded several different combustion regimes: one with sustained oscillatory flames, one with PPER, and then full extinction at very high excitation amplitudes. Phase-locked OH* chemiluminescence imaging and local temporal pressure measurements allowed quantification of the combustion-acoustic coupling through the local Rayleigh index. Similar behavior was observed for JP-8 and liquid synthetic fuel derived via the Fischer–Tropsch process, but with quantitative differences based on different reaction time scales. Estimates of the mean and oscillatory strain rates experienced by the flames during excitation assisted with interpreting specific relationships among acoustic, chemical, and fluid mechanical/straining time scales that can lead to a greater understanding of PPER.

1. Introduction

Acoustically coupled combustion instabilities have been a major challenge in the development of liquid rocket engines (LREs) and gas turbine engines over many decades [1,2]. Typically, these instabilities are spontaneously excited, and are characterized by large-scale, self-sustained pressure oscillations corresponding to a natural acoustic mode of the combustion chamber [2–4]. Large scale combustion instabilities are generally associated with a feedback cycle among temporal velocity oscillations u', pressure oscillations p', and oscillatory heat release q' in the reactive system, resulting in enhancement of the instability when the latter two parameters are in phase, or nearly so, per the well-known Rayleigh criterion [5]. Conversely, when pressure and heat release oscillations are out of phase with respect to one another, there is suggested to be a dampening of the instability [6]. For a reactive system, combustion instability can be described mathematically over an acoustic period T using the Rayleigh index G at a given location x as

$$G(x) = \frac{1}{T}\int_T p'(x,t)q'(x,t)dt, \tag{1}$$

where a positive G value denotes in-phase fluctuations of pressure and heat release and hence instability, while out-of-phase p' and q' lead to a negative G value and presumably stable combustion. Although the Rayleigh criterion has been shown to be consistent with naturally occurring thermo-acoustic instabilities in a large number of combustion systems [3], relating the bulk properties of the reactive system to the detailed acoustically-coupled flame dynamics is a topic of great interest, especially in the context of alternative fuels and their use in established combustor systems.

The single isolated burning fuel droplet represents a heterogeneous reactive process that provides a fundamental means to investigate condensed phase combustion relevant to both air-breathing and rocket engine systems. Evaporation at the droplet surface acts as a source of fuel vapor which reacts with the surrounding oxidizer, forming a diffusion flame structure. While in reactive liquid sprays the flame generally surrounds the spray

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https://doi.org/10.1016/j.combustflame.2017.10.019

Table 1
Theoretical and experimental resonant frequencies and wavelengths.

Speaker operation (180° out of phase) with PN at $x = 0$ cm					
		Theoretical		Experimental	
n	L	$f_{a,\,th}$ [Hz]	λ_{th} [cm]	$f_{a,\,exp}$ [Hz]	λ_{exp} [cm]
1	61	281	122	332	103
1	31	553	62	586	58.5
3	61	843	40.7	898	38.2

itself [7], causing the behavior of individual burning droplets to be a necessary component of models for such sprays [8]. Further, fundamental reactive processes associated with single droplet combustion are relevant to numerous multiphase reactive systems, including those shown to be susceptible to self-excitation of combustion instabilities [9–15].

Over the past decade our group has examined burning fuel droplets within a controlled acoustic environment to explore fundamental acoustically-coupled combustion processes in normal gravity and microgravity [16–18]. Recent normal gravity experiments quantify global flame properties (e.g., bulk flame deflections and mean droplet burning rate constant K) as well as temporally oscillatory parameters (e.g., acoustic pressure p' and flame OH* chemiluminescent intensity I') throughout the acoustic cycle, from which the Rayleigh index G may be extracted. For all four fuels examined in Sevilla-Esparza, et al. [16], bulk flame deflection characteristics are qualitatively consistent with the notion of a spatially variable acoustic radiation force causing the flame to deflect away from the pressure node (PN), as theorized by Tanabe et al. [19–21] for burning droplets and heated objects in microgravity. Enhancement of the droplet burning rate constant K under acoustic excitation in the vicinity of a PN, due to increased heat/mass transfer rates and larger velocity perturbations, has also been observed.

In normal gravity, buoyancy effects can become more significant than the influence of acoustic excitation, depending on the amplitude of acoustic excitation and the nature of the standing wave. As documented in Dattarajan, et al. [18,22], for example, methanol droplets situated near a pressure node or velocity antinode (VAN) in normal gravity produce only very moderate increases in burning rate, about 11–15% higher than for unforced, burning droplets. In microgravity, on the other hand, the absence of natural convection due to buoyancy reduces the unforced droplet's burning rate constant, so with the application of acoustic excitation, burning rate constants have been documented to increase by 85% to over 200% in the vicinity of a PN [18,19].

In our group's prior acoustically-coupled droplet combustion study [16], for both alcohol fuels (ethanol, methanol) and sooting hydrocarbons (JP-8, Fischer–Tropsch synfuel), the strongest degree of flame-acoustic coupling observed under moderate excitation occurred for droplets situated near a PN (or VAN) at relatively low frequency excitation (that is, 332 Hz, corresponding to the one-half wave mode for the waveguide), as long as a minimum amplitude of excitation was maintained, of the order $p'_{\max.} = 150$ Pa, where $p'_{\max.}$ represents the pressure amplitude at the PAN closest to the PN at $x = 0$. This corresponds to a VAN of $u'_{\max.} \approx 0.375$ m/s in the vicinity of the burning droplet. Preliminary studies [17], however, suggest that at higher amplitude excitation conditions, prior to complete flame extinction, fuel droplets can experience periodic partial extinction and reignition (PPER) of the oscillating flame structure. The present study more fully characterizes the acoustic excitation conditions (frequency, amplitude, and position relative to the PN) that lead to PPER, demonstrating for the first time that this phenomenon can occur with several alternative fuels under various acoustic forcing conditions. The present study discusses the phenomena in the context of prior theoretical predictions of PPER for strained opposed flow diffusion flames [23]. There is a focus in the present study on ethanol fuel in particular, but other hydrocarbon fuels were also explored which, together with accompanying local flame strain rate estimates, enabled a more fundamental understanding of acoustically-coupled flame dynamics.

2. Experiment setup and data processing

2.1. Acoustic field

The current study investigated the behavior of liquid hydrocarbon fuel droplets burning within a closed, optically-accessible cylindrical waveguide, operating at atmospheric pressure and with loudspeakers situated at each end (see Fig. 1), as used in prior experiments [16]. As is necessary for phase-locked, long duration imaging, the burning droplet was continuously fed through a borosilicate glass capillary by a syringe pump and fixed in place at the geometrical center of the waveguide tube. This enabled droplet combustion to take place over many minutes, rather than in a few seconds typical of non-fed, suspended droplet experiments. The acoustic drivers were forced at frequencies low enough to create effectively one-dimensional planar waves to which the burning droplets were exposed. When the loudspeakers operate out of phase ($\Delta\phi = 180°$), standing acoustic waves with a PN and corresponding VAN mid-way between the speakers can be created. The speakers could be moved relative to the geometrical center of the waveguide, with a fixed distance between them, to effectively alter the droplet location relative to the PN/VAN.

Forcing frequencies f_a of 332 Hz, 586 Hz, and 898 Hz were explored in the present study, corresponding to standing wave resonant conditions with a PN at the tube center for two different waveguide lengths. Earlier studies [16] explored even higher frequency excitation at 1500 Hz, but much higher amplitude forcing than practical would have been required to study such frequencies under the present conditions of interest. In order to create a standing wave resonance within the waveguide, f_a relates to the waveguide length (distance between speakers), L, and ambient speed of sound c by

$$f_a = \frac{nc}{2L}, \tag{2}$$

where n is an odd integer value corresponding to the resonance number (e.g. $n = 1, 3, 5$ etc.). A waveguide length of $L = 61$ cm was implemented for the forcing frequencies of 332 Hz ($n = 1$) and 898 Hz ($n = 3$), while $L = 31$ cm was implemented to permit $f_a = 586$ Hz to correspond to the first resonance. As described in Dattarajan et al. [18] and Sevilla-Esparza et al. [16], the speakers acted as non-perfectly reflecting boundaries, causing the actual and theoretical resonant frequencies and corresponding wavelengths ($\lambda = c/f_a$) to deviate from one another, as shown in Table 1.

In our previous work [16], the symmetry of the acoustic pressure profile within the waveguide was achieved through the use of two speakers bounding the waveguide, found to be superior to the prior speaker-reflector system [18,22]. In these prior experiments, sinusoidal forcing signals were generated using LabVIEW^{TM} in conjunction with a National Instruments USB-6251 data acquisition board (DAQ) and output to the speakers through a constant voltage gain stereo amplifier. To reduce asymmetries in the vicinity of the PN [24] and to more accurately obtain the desired pressure amplitude at the pressure antinode (PAN), a new tuning procedure was recently created [25], incorporating feedback control using a Kulite XCS-093-5D miniature pressure transducer located at the PAN between the droplet and closest speaker. The efficiency of this procedures is shown, for example, in Fig. 2(a)–(c), which demonstrate very close agreement between the experimental and theoretical (desired) acoustic pressure perturbation amplitude profiles for the three forcing frequencies at $p'_{\max.} = 200$ Pa.