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Isolated Single Droplet Combustion: FLEX Experiments Onboard the International Space Station

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1. Introduction

The spherically symmetric combustion of fuel droplets in microgravity provides an ideal experimental configuration for exploring fundamental combustion characteristics of liquid fuels, including chemical kinetics, soot formation, and other thermo-physical transport phenomena, a fact recognized by Kumagai in his pioneering study[1]. NASA initiated microgravity droplet combustion investigations in the early 1970's in the drop-towers at the NASA Glenn Research center[2], followed by experiments in the Space Shuttle, namely the Fiber-Supported Droplet Combustion (FSDC)[3], and the Droplet Combustion Experiment (DCE)[4, 5]. Subsequent to these studies, the Flame Extinguishment (FLEX) experiments, a series of isolated, single droplet (primarily) combustion experiments, were conducted onboard the International Space Station (ISS) by NASA, in collaboration with the international partners from Japan and Italy, using freely-floated (and fiber-supported) droplets of different pure fuels and fuel mixtures in pressures ranging from 0.5 to 5 atm. A brief summary of these experiments, and some of the significant results are presented in this report.

2. Experiments: MDCA Hardware

The FLEX experiments were performed using the Multi-User Droplet Combustion Apparatus (MDCA) in the Combustion Integrated Rack (CIR) facility located in the US Laboratory Module, Destiny of the ISS. Details of the experimental set up and operations can be found in[6-8], and only a brief summary is provided here. The combustion chamber in the CIR had an internal volume of 90 liter, and can be operated up to pressures of 9 atm using investigator-supplied premixed gas bottles containing the oxidizer/inert mixtures. The Fuel and Oxidizer Mixing Apparatus (FOMA) of the CIR allowed gas mixing to provide a predetermined oxygen/inert gas-mixture concentrations at a desired pressure at the start of each experiment. The droplet dispensing and deployment procedures were performed by the MDCA, one of the many experimental inserts the CIR facility can accommodate, using the opposed-needle deployment technique[6]. Droplet ignition was accomplished by a pair of retractable, opposed hot-wire igniters[7]. The power to the igniters can be varied depending upon the experimental requirements. The primary diagnostics during FLEX experiments were the backlit, black-and-white camera images of the droplet, and the OH* or CH* chemiluminescence images obtained using a Low Light Level Ultra-violet (LLLUV) camera package, both obtained at 30 frames per second. A color camera with zooming capability located inside the combustion chamber provided operational view of the droplet deployment and combustion processes. In addition, broad-band (0.4 to 100 μm) and narrow-band (5 to 7 μm) radiometers[8] were added later in the campaign along with a new LLLUV camera with a band-pass filter (390-490 nm) to visualize the cool flame radiation from formaldehyde chemiluminescence.

2.1 MDCA Experiment Operations

The MDCA apparatus was launched to the ISS in late 2008, and it remained in operation until September 2017. The first series of experiments using MDCA were the FLEX experiments, and it was primarily focused on spacecraft fire safety.

An alcohol (methanol) and an n-alkane (n-heptane) fuel droplets were burned in a diluent (CO_2, Helium, Xenon, N_2) substituted environments over a range of pressures to investigate the flammability boundaries. It was followed by the FLEX-2 experiments with the objective of studying fundamental aspects of droplet combustion. Pure fuels (n-octane, iso-octane, n-decane, ethanol), and fuel mixtures (n-heptane/hexadecane, propanol/glycerol, n-heptane/iso-octane, n-decane/propylbenzene) were tested to examine the liquid-phase mixing effects, soot formation, surrogate fuel mixture performance, and others. Ambient pressures varied from 0.5 to 3 atm. The next single droplet combustion experiment with MDCA was the FLEX-ICE-GA (FLEX-Italian Combustion Experiment-Green Air), conducted in collaboration with the Italian Space Agency (ASI), where n-heptane/ethanol and n-hexanol/n-decane fuel mixtures were tested. Fiber-supported droplet arrays studies were conducted in collaboration with JAXA and as a part of FLEX-2. The results from these droplet array investigations are presented elsewhere in this conference[9].

3. Experimental Observations and Discussions

The FLEX experiments, in general, can be grouped into three broad categories: alcohol fuel, pure alkane fuel, and fuel-mixture studies. We summarize the major results form these investigations in the following sections.

3.1. Alcohol Fuels

Unlike the alkane fuels, methanol droplets absorb water produced during gas-phase combustion into the liquid. This process leads to an increase in the water content of the liquid droplet to increase initially, and then the dissolved water begins to evaporate when its mass fraction reaches a critical value within the droplet leading to a diffusive extinction of the gas-phase flame. Larger methanol droplets (~ 3.5 mm in air), however, extinguish due to excessive radiative heat loss from the flame. Figure 1 shows the methanol droplet extinction diameter D_{ext} as a function of the initial droplet diameter D_0 for different inert concentrations in the ambient gas. Smaller droplets extinguish diffusively while the larger ones undergo radiative extinction. The transition from diffusive to radiative extinction depends strongly on the ambient oxygen mole fraction. More details of these observations can be found in[10, 11].

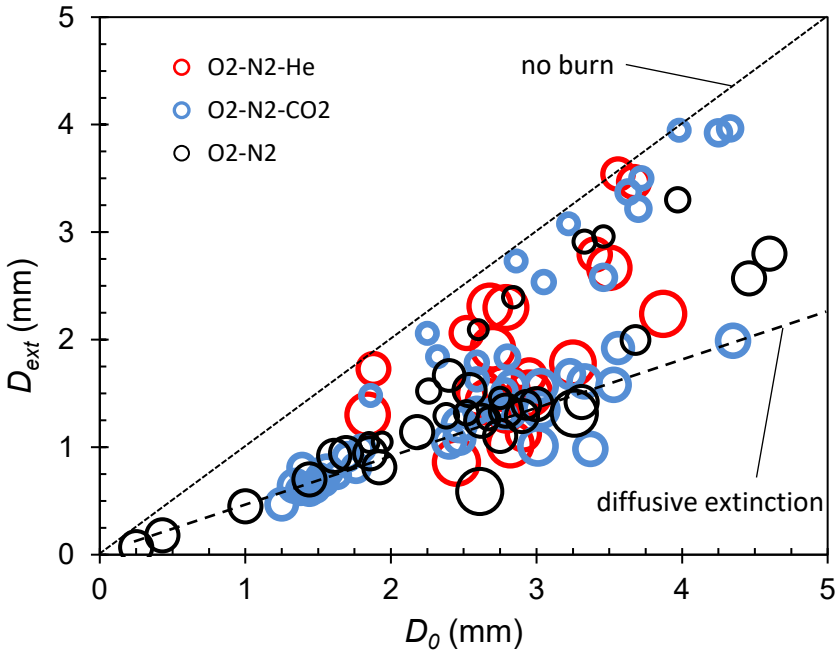

Fig. 1 Methanol droplet extinction diameter versus initial droplet diameter in diluent-substituted environments: the size of the bubble is proportional to ambient oxygen mole fraction.

3.2 N-alkane Fuel Investigations

One of the major findings from the FLEX series of experiments is the experimental observation of quasi-steady combustion and extinction of n-alkane droplets controlled by low-temperature cool flame chemistry [12]. Figure 2 shows

the burning history of an n-dodecane droplet in air at atmospheric pressure in microgravity obtained during the CFI experiments. Similar behavior was also observed for n-heptane, n-octane, and n-decane fuels. The various phenomenon of interest are, 1) droplet heat-up transience, 2) quasi-steady hot-flame combustion, 3) radiative flame extinction of the hot-flame, 4) quasi-steady cool flame combustion, 5) cool-flame extinction, and 6) vapor could formation due to condensing unburnt fuel.

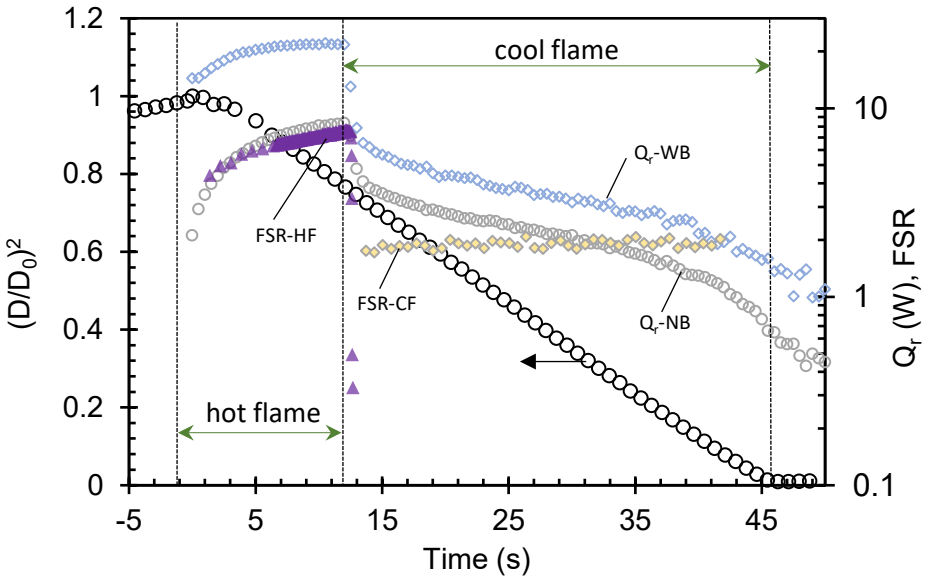

Fig. 2 N-dodecane droplet combustion history in air at 1atm: D_0 = 4.1 mm, wide-band radiation (Q_r-WB), narrow-band radiation (Q_r-NB), hot-flame standoff ratio (FSR-HF), and cool-flame standoff ratio (FSR-CF).

The droplet which is initially at the ambient temperature when deployed undergoes thermal expansion during the ignition period and unsteady heat up once the diffusion flame is formed around the vaporizing droplet [13]. The hot flame that is formed grows initially and experiences radiative extinction due to excessive heat loss from the flame zone [14-16]. Immediately following hot-flame extinction a cool flame forms around the droplet, with a lower flame stand-off ratio (FSR-CF ~ 2) compared to the hot flame (FSR-HF ~ 7), where FSR =D_f/D with D_f being the flame diameter and D being the instantaneous droplet diameter. The quasi-steady combustion of the cool flame continues until a diffusive extinction of the cool flame occurs[17]. Both the hot flame, and the cool flame extinctions are clearly identified from the sudden drop in radiometer outputs. A vapor cloud is found to form surrounding the droplet staring just prior to the cool flame extinction due to the condensing unburnt fuel and possibly other heavier hydrocarbons. Time-dependent numerical simulations with detailed chemistry that predicts both the hot and cool flame behaviors are now available in the literature [14,16,18]. Theoretical models with reduced and simplified chemistry have also been proposed for cool flame combustion and extinction [19-22]. It should be noted that for sufficiently small initial droplet sizes, the droplet burns with only the hot flame, and the vapor cloud formation at extinction is not observed. While the straight-chained normal alkane fuels readily exhibit low-temperature-controlled cool flame burning, it is not clear if the branched-chain fuels, such as iso-octane, do the same[23]. It has also been demonstrated during FLEX experiments and verified by numerical simulations that it is possible to directly ignite a cool flame, without involving hot-flame radiative extinction, by suitable selection of hot-wire ignition energy[24].

While the combustion processes described above is valid for ambient pressures below 2 atm, additional phenomena come into existence at elevated pressures. When the ambient pressure in the experiments is increased beyond approximately 2.0 atm, the cool flame reignites to a hot-flame, in repeating cycles, and the process becomes more complicated [25]. At elevated pressures it has also been found that a "warm flame" combustion can take palace with flame temperatures in between those of hot and cool flames[26,27]. Figure 3 illustrates the "warm" flame combustion of an n-dodecane droplet in air at 3 atm pressure. The visible flame is extinguished by radiative extinction (t~12.5 s), and a "warm" flame follows immediately after, which also extinguishes at t=39.1 s. The differences here compared to the cool flame shown in Fig. 2 are the FSR for the warm flame is much higher (~ 6.5), and the measured radiant energy loss by both the radiometers are comparable to that of the hot flame. It should also be noted that the warm flame oscillates before extinction.

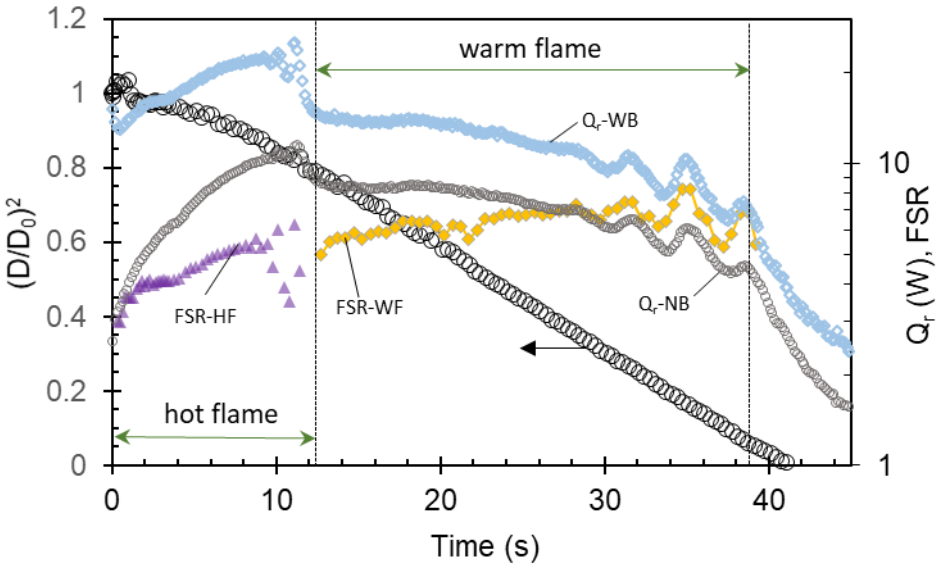

Fig. 3 N-dodecane droplet combustion history in air at 3 atm with warm flame: D_0 = 4.2 mm, wide-band radiation (Q_r-WB), narrow-band radiation (Q_r-NB), hot-flame standoff ratio (FSR-HF), and cool-flame standoff ratio (FSR-CF).

3.3 Fuel Mixture Studies

Droplets with bi-component fuel mixtures were studied during the FLEX-2, FLEX-ICEGA, and CFI campaigns. Avedisian and his co-workers studied a equi-volume mixture of n-heptane and iso-octane, a fuel mixture considered as a Primary Reference Fuel for gasoline. Smaller droplets (D_0 < 3 mm) exhibited only hot flame burning, while larger ones burned in two-stages, first with a hot flame followed by a cool flame. Numerical simulation with detailed chemistry showed good agreement with the experiments. It was also suggested, based on numerical calculations, that smaller droplets can be made to burn in the cool-flame mode by adding of small amounts of ozone to the ambient gas [28].

The FLEX-ICE-GA experiments investigated decane/hexanol (50-50 mixtures of by volume) bi-component droplets in air at pressures varying between 0.5 to 3 atm[8]. As in the case of pure decane fuel, the mixture exhibited quasi-steady cool flame combustion, and re-ignition of cool flames to hot flames at higher pressures. The addition of hexanol to decane caused the cool flame burning rates to be lower compared to pure decane and the cool flame extinction diameters were larger. Shaw and co-workers studied bi-component fuel droplets containing n-propanol-glycerol[29] and heptane-hexadecane[30] mixtures with the objective of understanding liquid phase fuel diffusivities. The volatility differences of the fuels in the mixture leads to a sudden flame contraction, when the more volatile fuel is almost exhausted, resulting in either complete flame extinction or subsequent cool flame combustion.

4. Concluding Remarks

The FLEX series of experiments have produced a wealth of data on droplet combustion in a long duration microgravity environment. Analysis of these data so far has shown many new phenomena previously undiscovered during droplet combustion studies, primarily stemming from the low and intermediate-temperature controlled chemical kinetics and their interaction with the transport mechanisms. Transient numerical computations with detailed chemistry have been successful in predicting qualitative trends of many of the observed phenomena, though quantitative comparison is still lacking, partially due to the inadequacies of the chemical kinetic mechanism employed. Theoretical description of the phenomena with simplified chemistry are still limited to the low temperature end of the chemistry. A unified theoretical framework with robust simplified mechanisms that can span all the different phenomena reported here is clearly needed, particularly at elevated pressures.

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