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On Droplet Combustion with Controlled Ambient Environments Under Microgravity

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Abstract

Many important progresses have been made in the study of droplet combustion under microgravity. First, it is found that the burning rates in normal gravity are 40% to 70% higher than the rates of the same fuel in reduced gravity. Also, under microgravity, the burning behavior varies greatly under different ambient environments, and can exhibit multi-stage burning with different temperature and droplet sizes. Significant results are reported from the flame extinguishment (FLEX) experiments aboard the International Space Station (ISS). For example, as the ambient oxygen mole fraction was reduced, the diffusive extinction droplet diameter increased, and the radiative extinction droplet diameter decreased. In addition, following radiative extinction of large alkane droplets, the droplet can continue to burn for an extended period of time with a low-temperature (cool) flame surrounding the droplet. These innovative experiments have provided a wealth of new data for improving the understanding of droplet combustion and related aspects of fire safety, as well as offering important measurements that can be used to test sophisticated evolving computational models and theories of droplet combustion.

Keywords: Droplet combustion; Microgravity; Multi-stage burning; Flame extinguishment

Introduction

Droplet combustion has been studied for decades due to its fundamental scientific importance and its practical usage. One simplification in the research is the assumption of spherical symmetry in which only one spatial dimension enters the description of the combustion process. This greatly facilitates the comparison of experiments with theoretical and numerical models (see for examples [1-5]). In [1], an early simplified model of droplet combustion of distillate fuels is studied in order to establish the fundamental principles involved. The experimental technique adopted has been to suspend a single drop of the fuel on a fine silica filament, and to measure with a cinematograph camera the rate of decrease in size during combustion in still air. In [2] the theory of combustion rate is investigated so that new combustion systems can be designed in a scientific manner, and the limits of improvement by varying fuel characteristics or operating conditions in existing system can be determined. Combustion of fuel droplets at various accelerations is studied using a combustion chamber that drops with constant acceleration in [3]. In [4], the behavior of methanol in carbon dioxide, helium, and xenon is explored and it is discovered that the droplets burn with much higher mole fractions of xenon than helium or carbon dioxide. Another notable statistic is that the burning rates in normal gravity are 40% to 70% higher than the rates of the same fuel in reduced gravity.

Recent experiments (flame extinguishment (FLEX) experiments) aboard the International Space Station (ISS) showed that following radiative extinction of large alkane droplets, the droplet can continue to burn for an extended period of time with a low-temperature (cool) flame surrounding the droplet [5]. Additional studies on the droplet combustion in microgravity have also been carried out experimentally [6,7], theoretically [8,9] and numerically [10,11]. In [6], experiments in which large droplets exhibit dual modes of combustion and extinction are observed. FLEX Experiment has been conducting isolated droplet combustion experiments aboard the ISS [7]. The overall goal of these experiments is to determine and analyze burning behavior as well as extinction mechanisms as a function of fuel, drop diameter, pressure, and etc.

In [8], a simplified model for droplet combustion in the partial-burning regime is applied to the cool-flame regime observed in droplet-burning experiments performed in the ISS. Good agreement is found with newly measured and numerically calculated flame standoff ratios in this droplet combustion supported by cool flames. In [9], quasi-steady combustion of droplets supported by cool-flame near diffusive extinction is studied. Finally, transient, spherically symmetric, combustion of single and multi-component liquid n-alkane droplets is numerically simulated with a model that includes gas phase detailed, multi-component molecular transport and complex chemical kinetics [10]. Model simulations are also carried out for experimental observations that characterize the transition time histories of multi-cycle, multi-stage burning behavior [11]. Transient sphero-symmetric droplet combustion modeling that considers multi-stage detailed kinetics, multicomponent diffusion, and spectral radiation is applied to analyze the experimental observations.

Burning behavior under controlled ambient environments

As mentioned earlier, the overall goal of FLEX experiments is to determine and analyze burning behavior as well as extinction mechanisms as a function of fuel, drop diameter, pressure, and etc. (see [7]). In order to achieve that, special experimental designs must be considered. First, one major experiment equipment is the Combustion Integrated Rack (CIR). It contains a combustion chamber, diagnostic equipment, a gas mixing system, the interface between the ISS and the Glenn Research Center (GRC) and the Multi-User Droplet Combustion Apparatus (MDCA) that produces and ignites the fuel droplets. The CIR is capable of operating anywhere between 0 and 9 atm, but this experiment conservatively only tested between 0.7 to 3.0 atm. The CIR accurately controls the ambient environment inside the chamber using the Fuel and Oxidized Mixing Apparatus (FOMA) that has gas bottles, pressure transducers, and mass flow controllers. The FLEX experiments use two different fuels: heptane, as a typical alkane fuel, and methanol, as a representative alcohol fuel. Initial droplet diameters are controlled, ranging from 1.5 to 5.0 mm. Ambient oxygen mole fractions range from 0.1 to 0.4. The ambient environments primarily contain oxygen and nitrogen diluted with carbon dioxide and helium.

To deploy a droplet into the CIR, fuel is dispensed between the tips of two needles then slowly drawn apart, so as not to cause spin in the droplet. After the droplet is deployed, two igniters burn the fuel. All the while, three different imaging systems are in action to capture droplet appearance: the High Bit-Depth Multispectral (HiBMs) Package, a Low Light Level Ultra-Violet (LLLUV) Package, and a color camera.

In [7], the experiments are carried out with different initial droplet diameters, ambient oxygen mole fractions and ambient pressures. The experiments show both radiative and diffusive extinction. The results reveal that as the ambient oxygen mole fraction is reduced, the diffusive extinction droplet diameter increases and the radiative extinction droplet diameter decreases.

Quasi-steady combustion processes are observed in between these two conditions. The experiments also define specific values for the limiting oxygen index for different ambient environments. One other new discovery is that large heptane droplets burn with a cool flame even after the visible hot flame radiatively extinguishes. These innovative experiments have provided a wealth of new data for improving the understanding of droplet combustion and related aspects of fire safety, as well as offering important measurements that can be used to test sophisticated evolving computational models and theories of droplet combustion.

From the experiments in [6], the droplet first undergoes normal burning with a visible flame surrounding the droplet and extinguishes radiatively at a relatively large droplet size. This event is followed by continued rapid quasi-steady vaporization of the droplet without any visible flame detected, which ends abruptly, at a point called ‘‘second-stage extinction’’ here, leaving behind a smaller droplet, which then either experiences normal time-dependent evaporation in the hot surrounding environment or sometimes apparently grows slightly through condensation of the vapor in the cloud that forms upon extinction, or through migration of the vapor-cloud particles to the droplet surface. This is the so called two-stage burning.

Simulation results in [12] show that both carbon dioxide and helium diluents can promote initiation of low temperature burning at smaller initial drop diameters than found with nitrogen as diluent. Small amounts of carbon dioxide and helium in the ambient is sufficient to activate the phenomena. The chemical kinetics dictating the second stage combustion and extinction process is also discussed.

Conclusion

Burning behavior as well as extinction mechanisms as a function of fuel, drop diameter, pressure, and etc. have been studied through the FLEX experiments aboard the ISS. It is discovered that large heptane droplets burn with a low-temperature (cool) flame even after the visible hot flame radiatively extinguishes. Also, as the ambient oxygen mole fraction is reduced, the diffusive extinction droplet diameter increases and the radiative extinction droplet diameter decreases. The normal burning and the radiative extinction can be followed by continued rapid quasi-steady vaporization of the droplet without any visible flame detected, which ends abruptly, at a point called ‘second-stage extinction’’. Simulation results show that both carbon dioxide and helium diluents can promote initiation of low temperature burning at smaller initial drop diameters than found with nitrogen as diluent. Additional theoretical and numerical studies are needed in order to better understand the complex burning dynamics in the droplet combustion under the microgravity.

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Conflict of Interest

No conflict of interest.

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