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Laminar Non-Premixed Flames of Gaseous Fuel Aboard the International Space Station

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Abstract: From late 2017 to early 2022, six independent studies with flames of gaseous fuels were conducted on the International Space Station (ISS) in the U.S. combustion research facility. An exploration of flames at the extremes of high sooting and high dilution was conducted with a coaxial coflow burner, where the fuel and oxidizer velocities were typically matched. An investigation of electric-field effects also used the same coflow burner as well as a simple gas-jet burner, with a circular electrode mesh, downstream of the burner, at voltages of either polarity up to 10 kV. A study focused on material flammability in a quiescent atmosphere emulated the burning of condensed-phased fuels using cylindrical burners with a flat perforated outlet instrumented to measure the heat flux to the burner, i.e., emulated fuel. Three studies of soot processes, flame dynamics, and low-temperature combustion used porous spherical burners, yielding a nominally one-dimensional flame structure. The objectives and selected findings of each investigation will be briefly discussed after a short review of the advantages of studying combustion in microgravity, earlier ISS research, and the experimental hardware and its operation.
Keywords: flames, microgravity, non-premixed, laminar

1. Introduction

Microgravity, i.e., apparent near weightlessness, is a unique environment for conducting combustion research. Many flames are dramatically influenced by the near elimination of buoyant convection, where the resulting effects are often advantageous [1-2]. For example, it is possible to create spherically symmetric flames enabling one-dimensional analysis. More generally, the effective elimination of flicker yields quasi-steady flames. Furthermore, the length scales are increased in microgravity flames facilitating analysis of their structure. Microgravity flames tend to have a much stronger sensitivity to their atmosphere than normal-gravity flames and exhibit a much broader range of characteristics. For example, the long residence times in microgravity flames can lead to strong soot production, but many microgravity flames are soot free due to radiative heat loss. Even neglecting soot, microgravity flames can be appropriate for studies of limit and stability behavior where chemical kinetics are important. It is also possible to study momentum-dominated flames at low velocities. And of course, microgravity is the appropriate environment for studies related to spacecraft fire safety.

Although microgravity combustion research has long been conducted in drop facilities and research aircraft flying parabolic maneuvers, spacecraft like the International Space Station (ISS) offer significant advantages. Drop durations, which are ~5 s or less in NASA drop facilities, are too short for soot to achieve quasi-steady conditions. They are also too short to first establish a flame and then vary conditions such as the flow rate, for example, to investigate stability or extinction limits. Meanwhile, low-momentum flames can be dramatically disturbed by the g-jitter present in aircraft testing, which is nominally ±0.02 g for a ~20 s duration. The jitter can be avoided by floating an experiment within the aircraft, but that reduces the test duration to mere seconds. As a result, space-based testing is often necessary to get microgravity conditions of sufficient duration and quality for combustion research.

The recent research was preceded by two earlier studies with laminar non-premixed flames of gaseous fuels conducted in the ISS' Microgravity Science Glovebox (MSG) using a crew-operated coflow apparatus consisting of a gas-jet burner centered within a fan-driven flow duct. On-orbit tests for the Soot Processes In Coflow Experiment (SPICE) of David L. Urban and Peter B. Sunderland were conducted in 2009 and 2012 [3]. ISS testing for the Structure & Liftoff In Combustion Experiment (SLICE) of Marshall B. Long, Mitchell D. Smooke, Fumiaki Takahashi, and Dennis P. Stocker was carried out in 2012 [4-7]. This pair of studies were in turn preceded by three investigations with non-premixed flames of gaseous fuels conducted during space shuttle missions in 1997 and 2003 [8-16]. The flames were similarly laminar, although one study featured mechanically induced vortices.

Tests for six independent experiments with flames of gaseous fuels were conducted on the ISS from Nov. 2017 to Feb. 2022 as part of the Advanced Combustion via Microgravity Experiments (ACME) project [2]. On-orbit preparations began in Sept. 2017, neglecting SLICE which was a planned precursor to ACME's Coflow Laminar Diffusion Flame (CLD Flame) investigation. Table 1 provides an overview of each study, where the first investigator listed is the Principal Investigator. Additional information, including preliminary findings, about each of the six experiments will be presented after a description of the experimental hardware and operations.

The ACME experiments are primarily focused on energy and environmental concerns, but there is a secondary emphasis with the Burning Rate Emulator (BRE) experiment on spacecraft fire prevention. The primary objective is to gain fundamental understanding that can enable improved efficiency and reduced emissions in practical combustion processes on Earth, for example through the development and verification of models for chemical kinetics and transport processes in computational simulations. In addition to enhanced performance, improved modeling capability can lead to reductions in the time and cost for combustor design. Some specific goals are to improve our understanding of combustion at fuel lean conditions where both optimum performance and low emissions can be achieved, cool flame chemistry, flame stability and extinction limits, materials flammability, oxygen-enriched combustion which could enable practical carbon sequestration, soot control and reduction, and the use of electric fields for combustion control.

2. Methods / Experimental

The ACME research was conducted using a single modular set of hardware with the Combustion Integrated Rack (CIR) [2]. That facility is shown on the left in Figure 1 with NASA astronaut Kate Rubins reconfiguring hardware for a different investigation on 3 Feb. 2021. The CIR provides a nominally 100-liter combustion chamber, gas delivery, venting, water cooling, imaging, and other general functions needed to carry out an array of combustion research. The facility was launched in 2008 and then used from 2009 to 2017 for a set of investigations featuring the combustion of liquid droplets. That research notably led to the discovery of non-premixed cool flames [17-22] which inspired ACME's Cool Flames Investigation with Gases (CFI-G).

ACME's chamber insert, which is ~0.4 m in diameter, provides common mounting for a variety of burners (but only one at a time) on the chamber axis. Tests were conducted with gas-

Table 1: Recent research on non-premixed flames of gaseous fuel conducted on the ISS (listed in chronological order)

Experiment	Investigators (*former)	Lead Russian collaborator	ISS operations	Selected references
Coflow Laminar Diffusion Flame (CLD Flame)	M.B. Long M.D. Smooke	S.S. Minaev	11/2017–02/2018 05/2018-09/2018 02/2021-03/2021	[23-25]
Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames)	D. Dunn-Rankin S. Karnani F.J. Weinberg* Z.-G. Yuan*	S.S. Minaev	03/2018-05/2018 09/2018-11/2018	[26]
Burning Rate Emulator (BRE)	J.G. Quintiere P.B. Sunderland J.L. de Ris	A.Y. Snegirev	01/2019-04/2019 07/2020–01/2021	[27-30]
Flame Design	R.L. Axelbaum P.B. Sunderland D.L. Urban B.-H. Chao*	S.M. Frolov	04/2019-07/2019 10/2021–02/2022	[31-33]
Structure and Response of Spherical Diffusion Flames (s-Flame)	C.K. Law S.D. Tse K.R. Sacksteder	V.V. Gubernov	07/2019–01/2020 04/2020-07/2020	*None*
Cool Flames Investigation with Gases (CFI-G)	P.B. Sunderland R.L. Axelbaum F.A. Williams	*None*	03/2021-06/2021 06/2021-10/2021	*None*

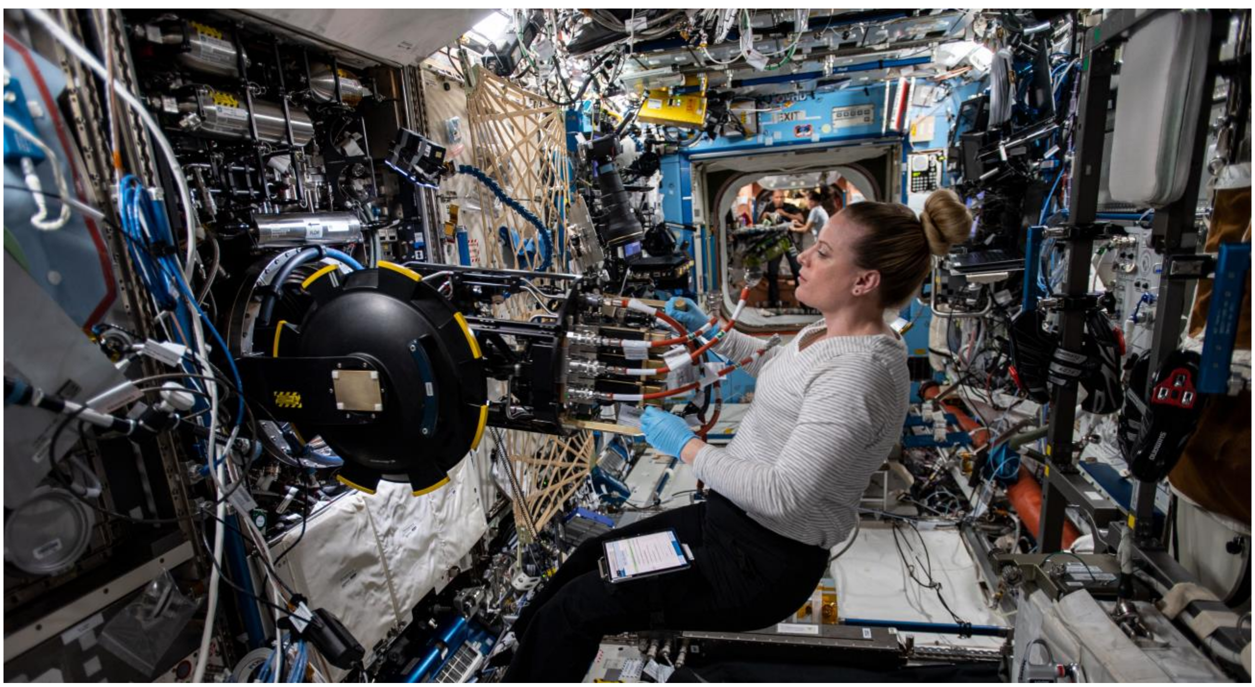

Figure 1: NASA astronaut Kate Rubins at the Combustion Integrated Rack (CIR) holding the chamber insert for the Advanced Combustion via Microgravity Experiments (ACME) suite of experiments during 3 Feb. 2021 preparations the next investigation [ISS064e029405, cropped]

jet, coflow, and spherical burners, plus a fourth type developed for the Burning Rate Emulator (BRE) investigation. The resistively heated igniter has a crew-exchangeable tip and arm (to accommodate the various burners) and its stepper-motor drive allowed for precise positioning and retraction from the flame.

The chamber insert includes three mass flow controllers, visible on the left of Fig. 2, for the delivery of fuel, oxidizer or inert (e.g., helium), and nitrogen to either the burner or the chamber. The crew exchanged the mass flow controllers to provide appropriate ranges to improve flow control and accuracy. The gas delivery system enabled on-orbit dilution of the fuel or oxidizer (but not both simultaneously), coflow, and inverse flames, where the oxidizer issued from the burner into the chamber filled with a gaseous fuel. Gases were also delivered premixed to the space station where that was necessary in some circumstances, such as the blending of different gaseous fuels. ACME tests were most often conducted with methane and ethylene where other fuels included hydrogen, ethane, propane, n-butane, and hydrogen/methane mixtures. Nitrogen dilution was common, but tests for the Structure and Response of Spherical Diffusion Flames (s-Flame) study were also conducted with helium as the inert in both the fuel and oxidizer.

The chamber insert provided an assortment of non-imaging instrumentation such as a crew-exchangeable array of thermopile detectors to measure thermal radiation. There is also a set of PhotoMultiplier Tubes (PMTs) which provided measurements of chemiluminescent emissions from the excited-state species CH* and OH* as well as a broadband measurement. A crew-exchangeable thermocouple rake, intended for studies of spherical flames, can be installed. While not shown in Fig. 2, the chamber insert is also equipped with a translating, crew-exchangeable array of 14-micron silicon carbide fibers for making measurements of flame temperature via Thin Filament Pyrometry (TFP) [e.g., 23-25,31-34].

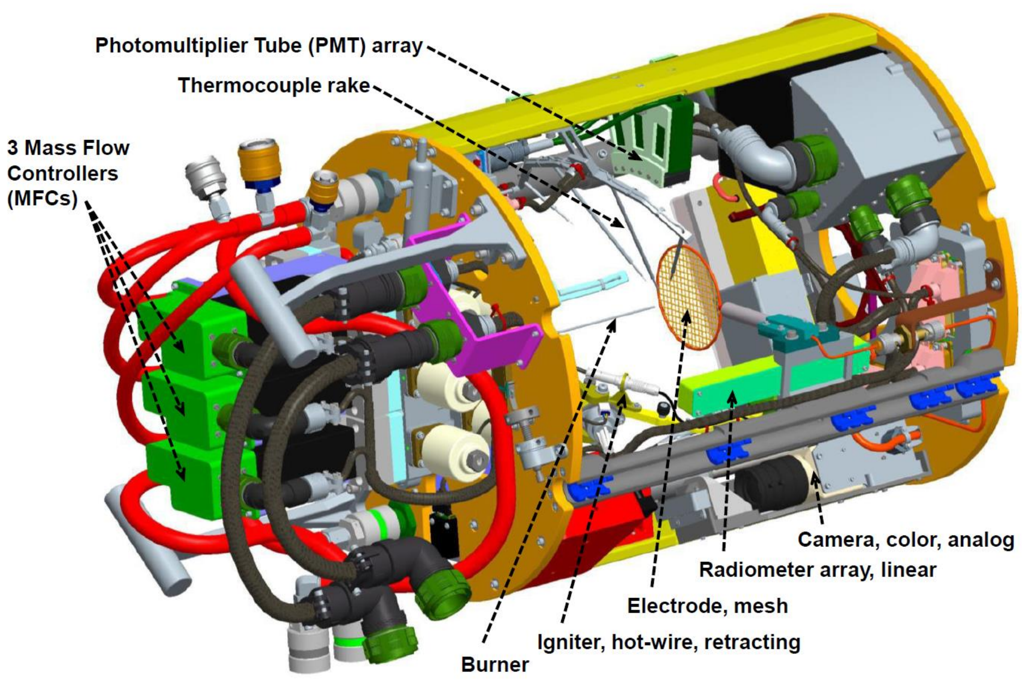

Figure 2: ACME chamber insert used within the CIR facility

Five different cameras and two illumination systems were used in the recent research, although usually only a fraction of them were used because of operational constraints. There is an analog camera mounted on the chamber insert from which color video was always downlinked in near real time during testing. The other four cameras were mounted around the periphery of the combustion chamber. A high-definition color camera, carefully characterized prior to launch, was always used. Both provide flame imaging, but the high-definition camera can furthermore be used to optically determine the CH* concentration, flame or soot temperature (via pyrometry), and soot volume fraction [e.g., 23-25]. The latter can also be determined using a gray-scale camera with an opposed collimated light source via a light extinction technique [36-37]. Two intensified cameras were used, one filtered for OH* emissions, while the other allows for imaging of CH* or alternately CH_2O* emissions associated with cool flame chemistry.

All ACME experiments are constant volume (rather than constant pressure) studies, where the chamber's free volume is approximately 83 liters depending on the installed hardware. The tests were typically only a few minutes in duration, limiting the pressure rise, vitiation of the chamber atmosphere, and acquisition of data which was an operational constraint.

The ACME experiments were configured, but not conducted, by the ISS crew. Instead, the tests were commanded from the ground, specifically from the NASA Glenn Research Center in Cleveland, Ohio. They were conducted in a mostly automated mode with pre-programmed scripts. But the role of the crew was critical and over 30 crew members from Canada, Germany, Italy, Japan, Russia, and the United States supported the four and half years of ACME operations. And about 50 people, including the investigators, were engaged in the ground operations.

Weekly operations typically included a two-shift day for testing, a two-shift day to downlink the resulting image data, and a day in which an ISS crew member prepared the hardware for the next test day. Replacement of gas bottles was the most common crew activity, where less frequent replacements included mass flow controllers and igniter tips. But the transition to a different experiment sometimes required many changes.

3. Results and Discussion

Past research, including that conducted in microgravity, had revealed shortfalls in the ability to accurately model flames at the extremes of fuel dilution, namely for sooty pure-fuel flames and dilute flames that are near extinction. The objective of the Coflow Laminar Diffusion Flame (CLD Flame) investigation is to extend the range of flame conditions that can be accurately predicted by developing and experimentally verifying chemical kinetic and soot formation submodels. The dependence of normal coflow flames on injection velocity and fuel dilution was carefully examined for flames at both very dilute and highly sooting conditions. Measurements including flame temperature, CH* concentration, soot temperature, and soot volume fraction were made of the structure of diluted methane and ethylene flames in an air coflow, where the fuel and air velocities are typically matched. Lifted flames are a focus of the research to avoid flame dependence on heat loss to the burner, where examples from ISS testing can be seen in Fig. 3a. The results are applicable to practical combustion issues such as turbulent combustion, ignition, and flame stability.

For sooty attached flames, preliminary results have revealed that the soot volume fraction can be several times greater in microgravity flames than in comparison normal-gravity flames. These microgravity flames are also taller and wider. Meanwhile, dilution limits for both methane and ethylene flames were extended in microgravity, where the microgravity flames are more stable, allowing for lifted flames at lower fuel concentrations.

An electric field can strongly influence flames because of its effect on the chemi-ions produced by the combustion. The direct ion transport and the induced ion wind can modify the flame shape, alter the soot or flammability limits, direct heat transfer, and reduce pollutant emission. The purpose of the Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames) study is to improve understanding of chemi-ionization in flames and the interplay between ion generation and ion-driven flows, and to explore how electric fields can be used to control non-premixed flames. The ISS tests were conducted burning pure and diluted methane and ethylene with both gas-jet and coflow flame configurations. An electric field of either polarity was generated by creating a high voltage differential (up to 10 kV) between the burner and a flat circular mesh above (i.e., downstream of) the burner. Measurements were made of the ion current through the flame and the flame's response to electric forcing as a function of the field strength, fuel, and fuel dilution.

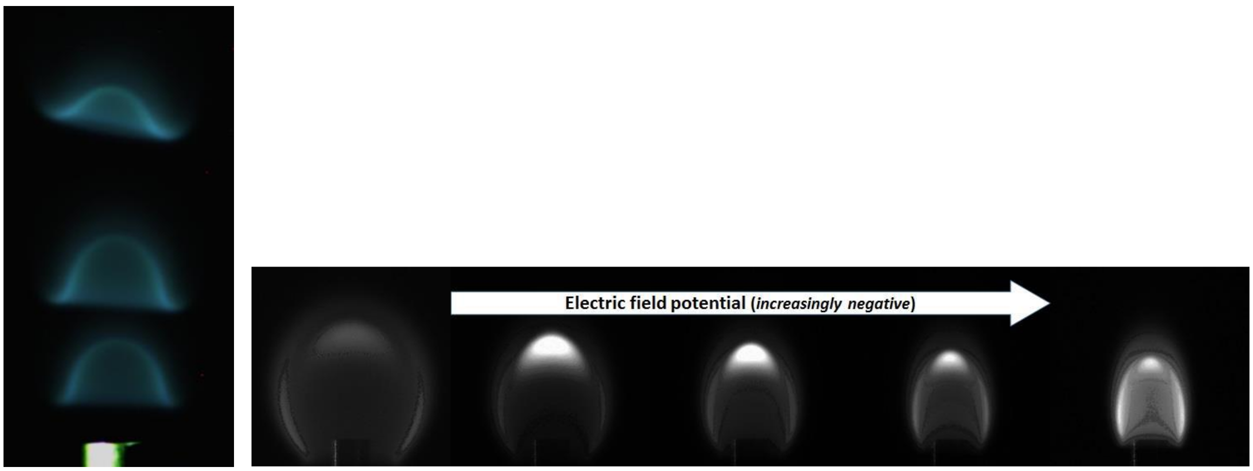

Figure 3: Gas-jet flames shown at different scales: (a) composite overlay of three dilute methane coflow flames as a function of the matched fuel/coflow velocity, (b) example of the effect of the electric field strength on the flame size where the downstream mesh was negatively charged

In contrast to normal-gravity tests, the microgravity flames exhibit a distinct peak ion current that corresponds to the most compact flame, where an example of the effect of the field strength on the flame size can be seen in Fig. 3b. Soot generation could be suppressed and more broadly there are clear correlations between the flame luminosity, combustion intensity, and ion current in the ISS data. It was found that highly diluted flames can be stabilized with very weak electric fields. But at high field strengths, the flames exhibited corona and arc discharges.

Unlike the other ACME experiments, the Burning Rate Emulator (BRE) research is focused on spacecraft fire prevention. More specifically, its objective is to improve our fundamental understanding of materials flammability in still atmospheres as a function of material properties. The research examines extinction behavior, the conditions needed for sustained combustion, and the relevance of existing flammability test methods for low and partial-gravity environments. A flat porous burner fed with gaseous fuel simulates the burning of solid and liquid fuels, where measurements were made of the thermal feedback (i.e., to the burner) upon which the vaporization of condensed-phase fuels is dependent. In the ISS tests, pure or nitrogen-diluted ethylene and methane were used to simulate the burning of materials such as plastics by matching properties including the heats of combustion and gasification, the surface temperature, and smoke point. Testing included atmospheres with elevated oxygen concentrations and reduced pressures being considered for future crew vehicles. An example dome-shaped flame can be seen in Fig. 4a.

It was found that low-momentum microgravity flames can burn for minutes in the absence of an air flow or flame spread. Although the flames can burn for minutes in elevated oxygen concentrations, like those being considered for future spacecraft, they were found to self-extinguish in concentrations below ~25% (by volume). While smaller flames can burn for minutes at elevated oxygen concentrations, larger flames were generally seen to self-extinguish within 1.5 minutes. Although ethylene flames at elevated oxygen concentrations can burn for minutes, methane flames were seen to self-extinguish within a minute.

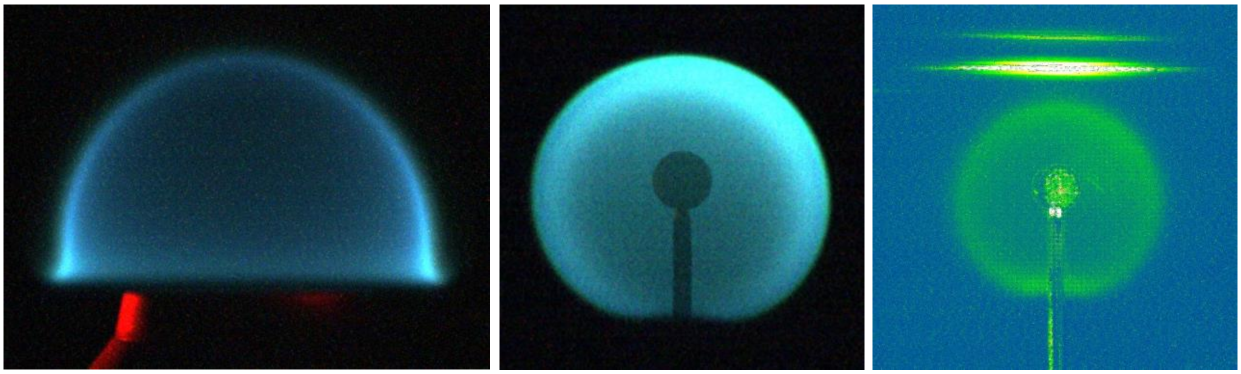

Figure 4: Low-momentum flames shown at different scales: (a) pure ethylene BRE flame where the burner is illuminated from the left in red, (b) inverse flame encompassing the porous spherical burner, with an oxygen/nitrogen mixture flowing from the burner into an ethylene/nitrogen atmosphere, (c) false-colored image of a diluted hydrogen flame, revealing the burner and glowing ceramic fibers for Thin-Filament Pyrometry

The primary goal of the Flame Design experiment is to improve fundamental understanding of soot inception and control and thereby enable the optimization of oxygen-enriched combustion and the 'design' of non-premixed flames that are both robust and soot free. A secondary goal is to obtain detailed quasi-steady measurements and evaluate the possible existence of steady flames. The tests were conducted with various concentrations of ethylene and oxygen to determine the role of the flame structure on the soot inception. The effect of the flow direction on soot formation was assessed by studying both normal flames and inverse flames, in which the oxidizer flowed from the burner into an atmosphere of gaseous fuel. The burner, including its supply tube, can be seen within an inverse flame in Fig. 4b.

As expected in the normal-flame ISS testing, the flame size increases with reactant flow rate and decreases with ambient oxygen concentration. Very small flames have low radiative loss and asymptotically approach steady-state behavior, where one flame lasted over 14 minutes until it was terminated due to operational constraints. In contrast, large flames increase in size over time until the flame extinguishes because of radiative heat loss. Before extinction, these flames experience an unstable oscillatory mode, in which they partially quench and reform. The oscillations grow in magnitude until the flame fully extinguishes.

The goal of the Structure and Response of Spherical Diffusion Flames (s-Flame) investigation is to advance our ability to predict the structure and dynamics of non-premixed spherical flames, potentially through modification of kinetic and/or transport sub-models. The spherical flames were ignited and allowed to transition naturally toward extinction, where a specific objective is to identify the extinction limits for both radiative and convective extinction (i.e., at high and low system Damköhler numbers, respectively). Tests were conducted with either nitrogen or helium as the diluent in both the fuel and chamber atmosphere. The fuel gases included hydrogen, methane, hydrogen/methane mixtures, and ethylene where an example hydrogen flame can be seen in Fig. 4c.

Both radiative and kinetic (i.e., convective) extinction of the spherical flames appear to have been observed. Radiative extinction seems to occur at high flow rates and kinetic extinction at low flow rates. The latter may seem counterintuitive but at low flow rates the flames are close to the burner where the velocities are highest. With helium, rather than nitrogen, dilution of both the fuel and oxygen, the extinction limits are shifted and kinetic extinction is generally difficult to discern.

The purpose of Cool Flames Investigation with Gases (CFI-G), selected for spaceflight by the Center for the Advancement of Science in Space (CASIS) and the National Science Foundation (NSF), is to observe non-premixed quasi-steady spherical cool flames on porous burners. Non-premixed cool flames had been discovered in droplet combustion research conducted in the CIR in 2012 but droplet combustion involves unsteady burning rates. Although ignition and flame propagation in engines depend on cool flames, computational tools used to design the engines neglect cool flame chemistry. Advances in low-temperature kinetic mechanisms could enable cleaner burning, more efficient internal combustion engines. Tests were carried out with normal- and inverse-flame tests of ethane, propane, and n-butane.

Cool flames were discovered in normal-flame CFI-G testing with n-butane as can be seen in Fig. 5 which features a sequence of images from an intensified camera filtered for formaldehyde emissions. As expected, the cool flames are significantly smaller than the corresponding hot flames.

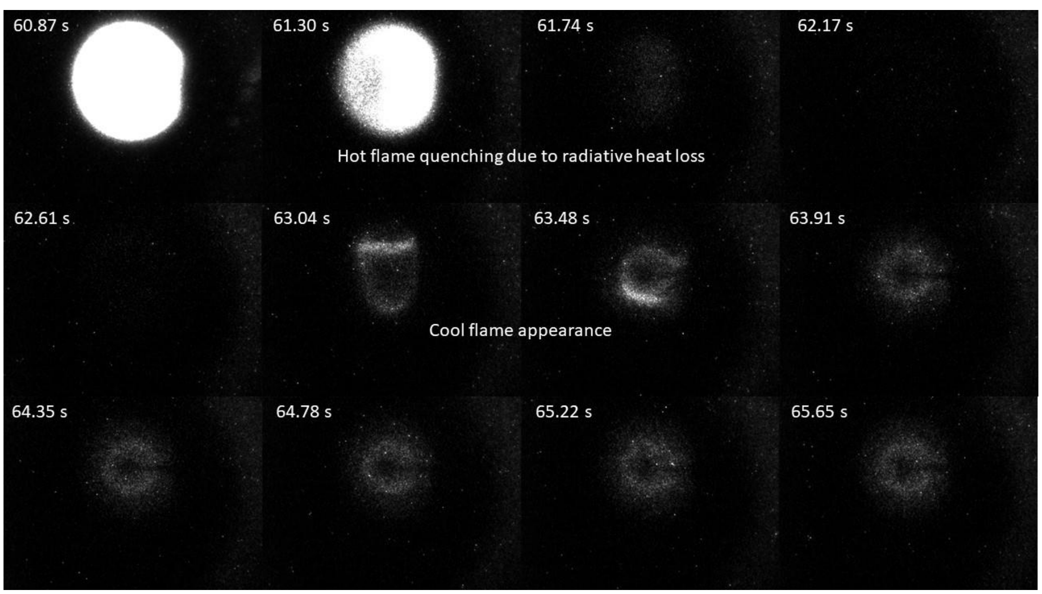

Figure 5: Appearance of a cool flame, in intensified imaging, after the hot flame quenches in a normal-flame test with diluted n-butane

4. Conclusions

When ACME's ISS testing ended in Feb. 2022, over 1,500 flames were ignited for its six experiments. Early results have been presented and published and more papers will follow [e.g., 23-33]. ACME's open-source data is gradually being made available through NASA's Physical Sciences Informatics website. Data from the E-FIELD Flames and s-Flame investigations, the first studies for which ISS testing was completed, are currently available online. CIR operations have shifted to the Solid Fuel Ignition and Extinction (SoFIE) project which is focused on flammability, flame spread, and spacecraft fire safety [2].

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