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Recent Research on Flames of Gaseous Fuel Aboard the International Space Station

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Abstract

Research for a set of six independent experiments with flames of gaseous fuels has been carried out on the International Space Station (ISS) since 2017 using the Combustion Integrated Rack (CIR) and a set of modular hardware. While ISS testing has been completed for most of the studies in the Advanced Combustion via Microgravity Experiments (ACME) project, it is expected to continue into 2022. The objectives and selected findings for each investigation are briefly discussed after a short review of the advantages of studying combustion in microgravity, previous research conducted in space, and the experimental hardware and its operation.

1. Introduction

1.1 Combustion in Microgravity

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 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.

1.2 Previous Research on Flames of Gaseous Fuels Conducted in Space

Five different experiments burning gaseous fuels were conducted during space shuttle missions in 1997 and 2003. Three of those studies are similar to the recent ISS investigations addressed in this paper in that they featured non-premixed flames in which the fuel and oxygen were separated by the flame sheet. More specifically, in the three investigations the fuel issued from a burner into an oxidizer atmosphere. Each of the other two studies instead featured premixed flames in which a combustion vessel was filled with a mixture of the reactants. In terms of facilities, three of the five studies were conducted in the Combustion Module (CM), a space shuttle precursor to the ISS' Combustion Integrated Rack (CIR), while one was conducted in the Middeck Glovebox (MGBX) and another in a Get-Away Special (GAS) canister in the shuttle's cargo bay. The latter investigation was automated, while the other four were crew operated.

Two crew-operated experiments with gaseous fuels were subsequently conducted in the ISS' Microgravity Science Glovebox (MSG) with an improved version of the Enclosed Laminar Flames (ELF) hardware used in a 1997 shuttle mission. Both featured non-premixed flames, where there have thus far been no investigations with premixed flames conducted on the ISS. The Soot Processes In Coflow Experiment (SPICE) was a follow-on to Laminar Soot Processes (LSP), although it was carried out without Prof. G. Faeth, the LSP Principal Investigator, who unfortunately died before SPICE's launch.

These seven past investigations are briefly summarized in Table 1, where they are listed in chronological order. The first person listed for each experiment was its Principal Investigator. Meanwhile, STS is an abbreviation for the space shuttle, i.e., Space Transportation System. The experiments with premixed flames are of limited relevance to the recent research addressed in this paper and are shown in italics.

Table 1 Past research on non-premixed and *premixed* flames of gaseous fuels conducted in space

Experiment	Investigator(s)	Facility	Mission (year)	Selected references
Laminar Soot Processes (LSP)	Gerard M. Faeth	CM	STS-83 (1997), STS-94 (1997), STS-107 (2003)	3-8)
Structure Of Flame Balls At Low Lewis-number (SOFBALL)	*Paul D. Ronney*	*CM*	*STS-83 (1997), STS-94 (1997), STS-107 (2003)*	*9-13)*
Enclosed Laminar Flames (ELF)	Lea-Der Chen Dennis P. Stocker John E. Brooker	MGBX	STS-87 (1997)	14-17)
Turbulent Gas-jet Diffusion Flames (TGDF)	M. Yousef Bahadori Uday G. Hegde	GAS	STS-87 (1997)	18-23)
Water-Mist Fire Suppression (Mist)	*J. Thomas McKinnon* *Angel Abbud-Madrid*	*CM*	*STS-107 (2003)*	*24)*
Soot Processes In Coflow Experiment (SPICE)	David L. Urban Peter B. Sunderland	MSG	ISS (2009, 2012)	25-28)
Structure & Liftoff In Combustion Experiment (SLICE)	Marshall B. Long Mitchell D. Smooke Fumiaki Takahashi Dennis P. Stocker	MSG	ISS (2012)	29-32)

1.3 Advanced Combustion via Microgravity Experiments (ACME)

Tests for six independent experiments with flames of gaseous fuels have been conducted on the ISS as part of the Advanced Combustion via Microgravity Experiments (ACME) project [2, 33-35]. On-orbit preparations began in Sept. 2017, but the Structure & Liftoff In Combustion Experiment (SLICE), a planned precursor to ACME's Coflow Laminar Diffusion Flame (CLD Flame) investigation, was conducted in 2012. Table 2 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. Final testing remains for two of the studies, where it is tentatively expected that all ISS testing for ACME will be completed in 2022.

The ACME experiments are primarily focused on energy and environmental concerns, but there is a secondary emphasis with the 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.

Table 2 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)	Marshall B. Long Mitchell D. Smooke	Sergey S. Minaev	Nov. 2017–Feb. 2018 May-Sept. 2018 Feb.-March 2021	36-37)
Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames)	Derek Dunn-Rankin Sunny Karnani Felix J. Weinberg* Zeng-Guang Yuan*	Sergey S. Minaev	March-May 2018 Sept.-Nov. 2018	38-40)
Burning Rate Emulator (BRE)	James G. Quintiere Peter B. Sunderland John L. de Ris	Alexander Y. Snegirev	Jan.-April 2019 July 2020–Jan. 2021	41-45)
Flame Design	Richard L. Axelbaum Beei-Huan Chao* Peter B. Sunderland David L. Urban	Sergei M. Frolov	April-July 2019 ? - ?	46-48)
Structure and Response of Spherical Diffusion Flames (s-Flame)	Chung K. Law Stephen D. Tse Kurt R. Sacksteder	Vladimir V. Gubernov	July 2019–Jan. 2020 April-July 2020	*None*
Cool Flames Investigation with Gases (CFI-G)	Peter B. Sunderland Richard L. Axelbaum Forman A. Williams	*None*	March-June 2021 June 2021 - ?	*None*

2. Experimental

2.1 Hardware

The ACME research is conducted using a single modular set of hardware with the Combustion Integrated Rack (CIR) [2, 33, 49]. That facility is shown in Figures 1 and 2 with Japanese astronaut Norishige Kanai when he reconfigured the optics for one of its cameras on 5 March 2018. 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 [50-55] and inspired ACME's Cool Flames Investigation with Gases (CFI-G).

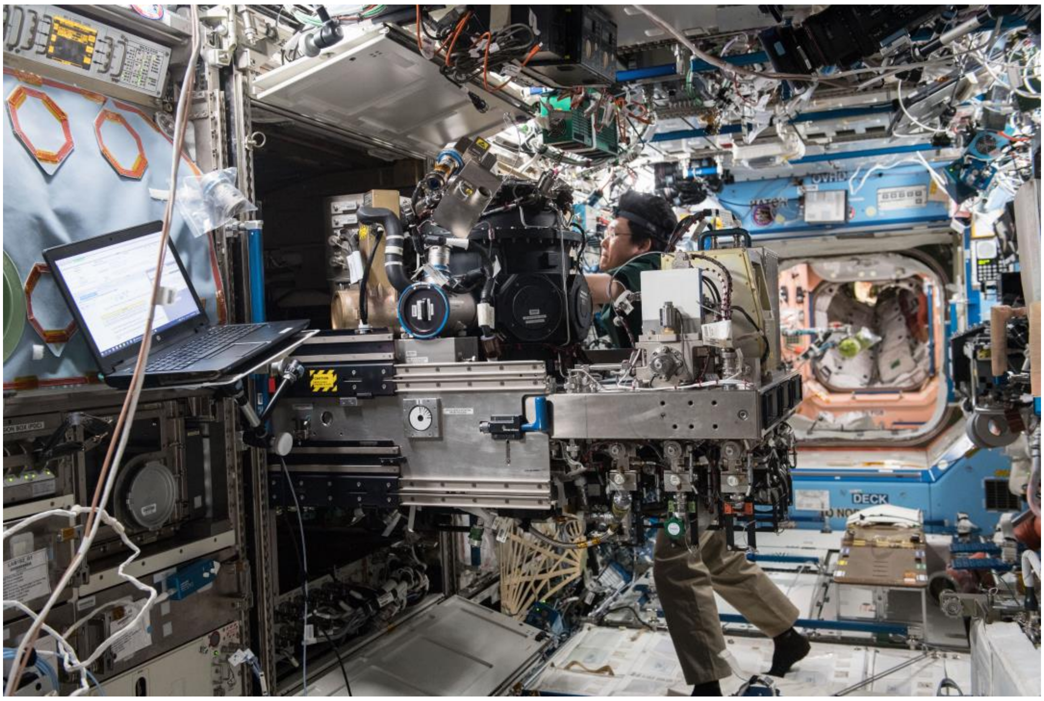

Fig. 1 Japanese astronaut Norishige Kanai reconfiguring a Combustion Integrated Rack (CIR) camera [ISS055e096568]

Fig. 2 CIR facility returned to its normal configuration by Japanese astronaut Norishige Kanai [ISS055e096658]

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 have been conducted with gas-jet, coflow, and spherical burners, in addition to 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 allows for precise positioning and retraction from the flame. The insert is partially withdrawn from the chamber in Figure 3, taken on 10 May 2019 when Canadian astronaut David Saint-Jacques replaced the igniter tip. Although relatively small, a porous spherical burner can be seen in the photo.

Fig. 3 Canadian astronaut David Saint-Jacques working with the ACME chamber insert [ISS059e060847]

The chamber insert includes three mass flow controllers, visible on the left of Fig. 4, for the delivery of fuel, oxidizer or inert (e.g., helium), and nitrogen to either the burner or the chamber. The crew can exchange the mass flow controllers to provide appropriate ranges to improve flow control and accuracy. The gas delivery system enables on-orbit dilution of the fuel or oxidizer (but not both simultaneously), coflow, and inverse flames, where the oxidizer issues from the burner into the chamber filled with a gaseous fuel. Gases are also delivered premixed to the space station where that is necessary in some circumstances, such as the blending of different gaseous fuels. ACME tests have been most often conducted with ethylene (C_2H_4) and methane (CH_4) where other fuels used included hydrogen (H_2), ethane (C_2H_6), propane (C_3H_8), n-butane (C_4H_{10}), and hydrogen/methane mixtures. Nitrogen dilution is 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.

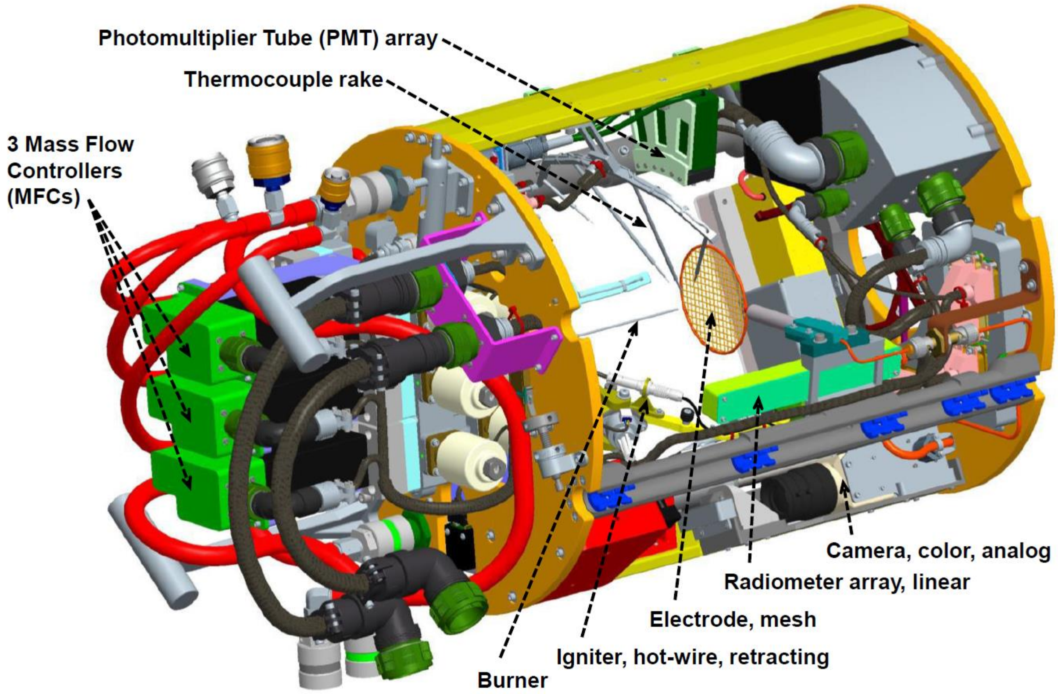

Fig. 4 Advanced Combustion via Microgravity Experiments (ACME) chamber insert used within the CIR facility

The chamber insert provides 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) providing 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. 4, the chamber insert is also equipped with a translating, crew-exchangeable array of 14-micron silicon carbide (SiC) fibers for making measurements of flame temperature via Thin Filament Pyrometry (TFP) [e.g., 36-37, 46-48, 56].

Five different cameras and two illumination systems have been used in the recent research, although usually only a fraction of the cameras have been used because of operational constraints. There is an analog camera mounted on the chamber insert for which the color video is always downlinked during testing in near real time. The other four cameras are mounted around the periphery of the black combustion chamber seen in the center of Fig. 1. A high-definition color camera, carefully characterized prior to launch, is always used. Both provide flame imaging, but the high-definition camera can furthermore be used to optically determine the CH* concentration, flame and soot temperature (via pyrometry), and soot volume fraction [e.g., 36-37, 46-48, 56-57]. The latter can also be determined using a gray-scale camera with an opposed collimated light source via a light extinction technique [58-59]. Two intensified cameras have been used, one filtered for OH* emissions, while the other allows for imaging of CH*, the primary source of blue light in hydrocarbon flames, or formaldehyde (CH_2O) emissions associated with cool flame chemistry.

2.2 Procedure

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 are typically only a few minutes in duration, limiting the pressure rise, vitiation of the chamber atmosphere, and acquisition of data which is an operational constraint.

The ACME experiments are configured, but not conducted, by the ISS crew. Instead, the tests are commanded from the ground, specifically from the NASA Glenn Research Center in Cleveland, Ohio. They are conducted in a nominally automated mode using pre-programmed scripts. But the role of the crew is critical and thus far 30 different crew members from Canada, Germany, Italy, Japan, Russia, and the United States have supported ACME operations.

Weekly operations have 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 prepares the hardware for the next test day. Replacement of gas bottles is the most common crew activity, where less frequent replacements include mass flow controllers and igniter tips. But the transition to a different experiment can require many other changes, such as the reconfiguration of imaging systems as shown in Fig. 1.

3. Experiments and Selected Findings

3.1 Coflow Laminar Diffusion Flame (CLD Flame)

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. This investigation's objective 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 is carefully examined for flames at both very dilute and highly sooting conditions. Measurements including flame temperature, CH* concentration, soot temperature, and soot volume fraction are 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. 5. The results are directly 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.

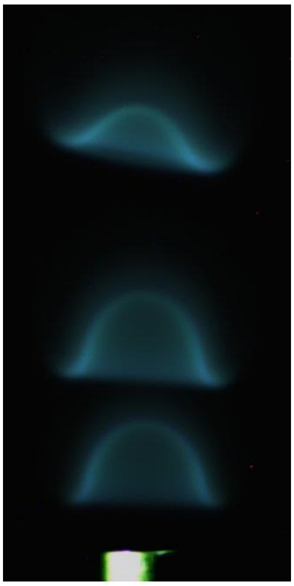

Fig. 5 Composite overlay of three dilute methane coflow flames as a function of the matched fuel/coflow velocity

3.2 Electric-Field Effects on Laminar Diffusion Flames (E-FIELD Flames)

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. This experiment's purpose is to improve understanding of chemi-ionization in flames and the interplay between ion generation & ion-driven flows and 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.

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. 6. 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.

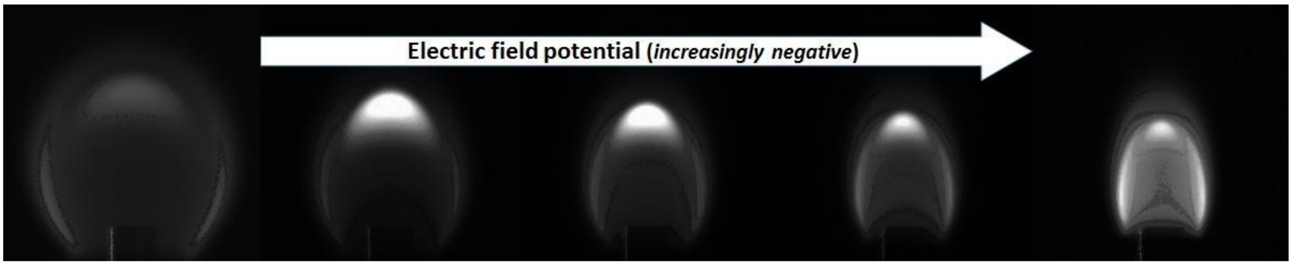

Fig. 6 Example of the effect of the electric field strength on the flame size where the mesh was negatively charged

3.3 Burning Rate Emulator (BRE)

Unlike the other ACME experiments, this study 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 are 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. 7.

Low-momentum microgravity flames can burn for minutes in the absence of an air flow or flame spread. While 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. While ethylene flames at elevated oxygen concentrations can burn for minutes, methane flames were seen to self-extinguish within a minute.

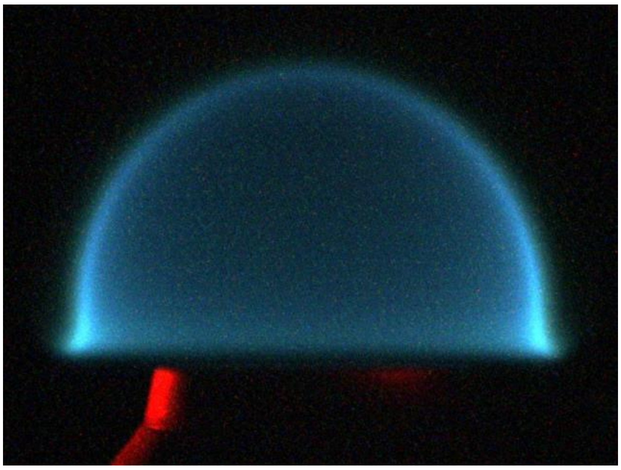

Fig. 7 Pure ethylene BRE flame, where the burner is illuminated from the left in red

3.4 Flame Design

The primary goal of this 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. This research will furthermore assess whether the stoichiometric mixture fraction can characterize soot and flammability limits for non-premixed flames like the equivalence ratio serves as an indicator of those limits for premixed flames. Tests are 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 is assessed by studying both normal flames and inverse flames. The burner, including its supply tube, can be seen within a normal flame in Fig. 8. Although the normal-flame tests have been completed, the inverse-flame testing has yet to begin.

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. 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.

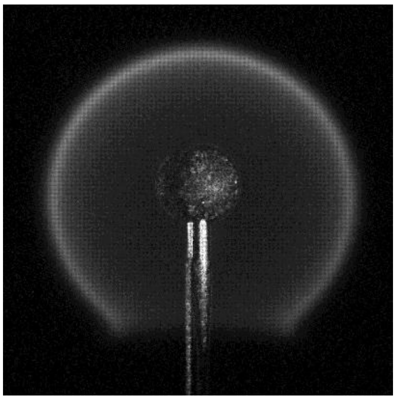

Fig. 8 Pure ethylene spherical flame, encompassing the porous spherical burner, from normal-flame testing

3.5 Structure and Response of Spherical Diffusion Flames (s-Flame)

This study's goal 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. 9.

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.

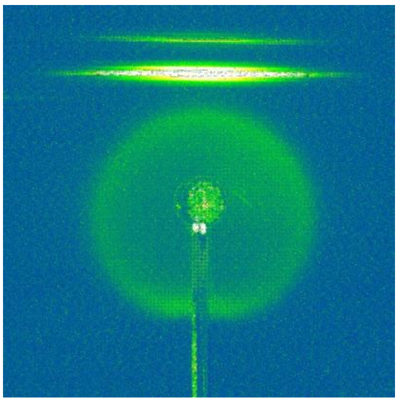

Fig. 9 False-colored image of a diluted hydrogen flame, revealing the burner and glowing ceramic TFP fibers

3.6 Cool Flames Investigation with Gases (CFI-G)

This purpose of this experiment, 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. As previously mentioned, non-premixed cool flames were 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 cool flames kinetic mechanisms could enable cleaner burning, more efficient internal combustion engines. Testing is underway where the normal- and inverse-flame tests are being conducted with ethane, propane, and n-butane.

Cool flames were discovered in CFI-G testing with n-butane as can be seen in Fig. 10 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.

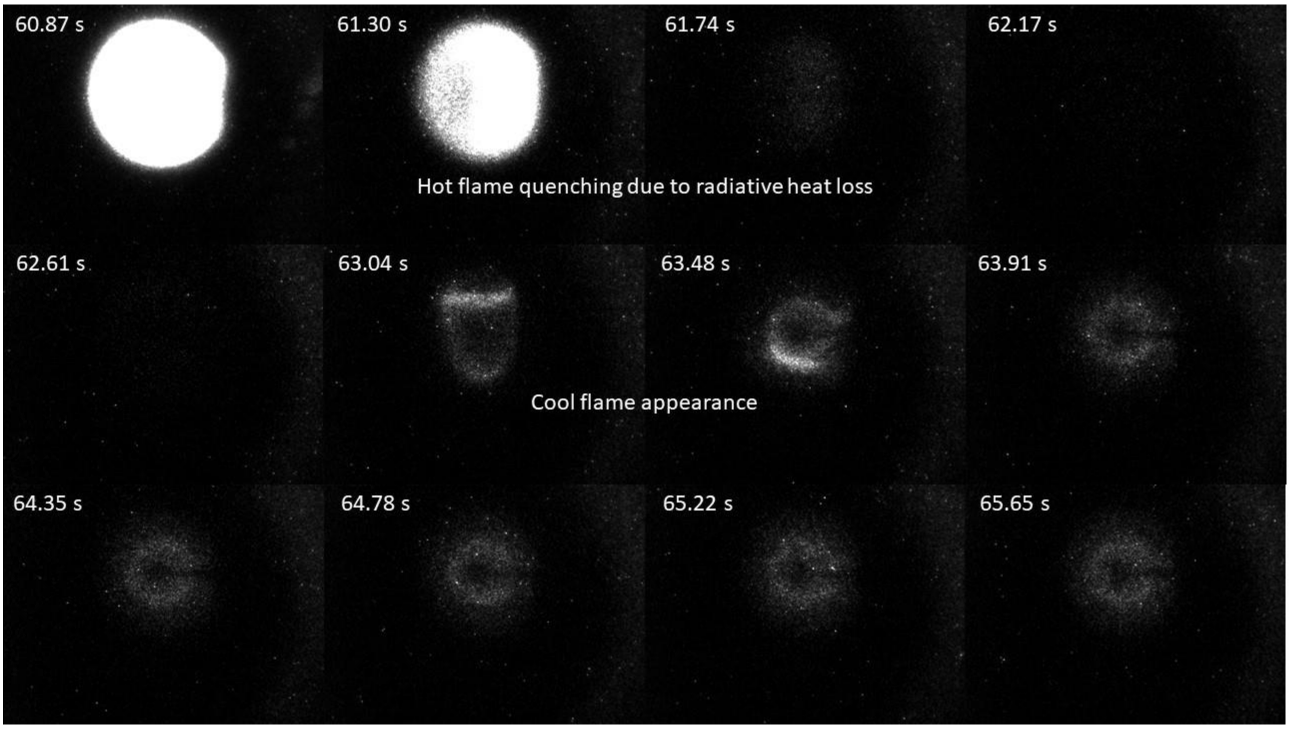

Fig. 10 Appearance of a cool flame after the hot flame quenches in a normal-flame test with diluted n-butane

4. Concluding Remarks

ACME testing is still underway, but well over a thousand flames have been ignited for the six experiments since science operations began in Nov. 2017. Early results have been presented and published [36-48] and more papers will follow. ACME's open-source data and results are gradually being made available through NASA's Physical Sciences Informatics website [60]. As an example, data from the E-FIELD Flames investigation, the first study for which the ISS testing was completed, is now available online. It is tentatively expected that all ISS testing for ACME will be completed in 2022, after which the CIR facility will be used for the experiments of the Solid Fuel Ignition and Extinction (SoFIE) project [61] which is focused on flammability, flame spread, and spacecraft fire safety.

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References

1) H. D. Ross, ed.: Microgravity Combustion: Fire in Free Fall, Academic Press, London, UK, 2001.
2) S. A. Gokoglu, D. L. Dietrich, D. P. Stocker, P. V. Ferkul, S. L. Olson and M. C. Hicks: ISS Researcher's Guide to: Combustion Science, 2015, https://www.nasa.gov/connect/ebooks/researchers_guide_combustion_science_detail.html.
3) D. L. Urban, Z.-G. Yuan, P. B. Sunderland, G. T. Linteris, J. E. Voss, K.-C. Lin, Z. Dai, K. Sun and G. M. Faeth: AIAA J., **36** (1998) 1346.
4) K.-C. Lin, G. M. Faeth, P. B. Sunderland, D. L. Urban and Z.-G. Yuan: Combust. Flame, **116** (1999) 415.
5) D. L. Urban, Z.-G. Yuan, P. B. Sunderland, K.-C. Lin, Z. Dai and G. M. Faeth: Proc. Combust. Inst., **28** (2000) 1965.
6) G. M. Faeth: Microgravity Combustion: Fire in Free-Fall, Academic Press, London, UK, 2001, 83.
7) C. Aalburg, F. J. Diez, G. M. Faeth, P. B. Sunderland, D. L. Urban and Z.-G. Yuan: Combust. Flame, **142** (2005) 1.
8) F. J. Diez, C. Aalburg, P. B. Sunderland, D. L. Urban, Z.-G. Yuan and G. M. Faeth: Combust. Flame, **156** (2009) 1514.
9) P. D. Ronney, M.-S. Wu, H. G. Pearlman and K. J. Weiland: AIAA J., **36** (1998) 1361.
10) M.-S. Wu, J.-B. Liu and P. D. Ronney: Proc. Combust. Inst., **27** (1998) 2543.
11) J. D. Buckmaster and P. D. Ronney: Proc. Combust. Inst., **27** (1998) 2603.
12) M. Abid, M.-S. Wu, J.-B. Liu, P. D. Ronney, M. Ueki, K. Maruta, H. Kobayashi, T. Niioka and D. M. VanZandt: Combust. Flame, **116** (1999) 348.
13) O. C. Kwon, M. Abid, J.-B. Liu, P. D. Ronney, P. M. Struk and K. J. Weiland: 42nd AIAA Aerospace Sciences Meeting, Reno, NV, 5-8 Jan. 2004.
14) J. E. Brooker, D. P. Stocker and L.-D. Chen: Central States Meeting of the Combustion Institute, Lexington, KY, 31 May - 2 June 1998.
15) J. E. Brooker, K. Jia, D. P. Stocker and L.-D. Chen: Fourth U.S. Microgravity Payload: One Year Report, Sept. 1999, 151.
16) K. Jia and L.-D. Chen: 38th AIAA Aerospace Sciences Meeting, Reno, NV, 10-13 Jan. 2000.
17) R. Venuturumilli and L.-D. Chen: Fuel **88** (2009) 1435.
18) U. Hegde, M. Y. Bahadori and D. P. Stocker: 37th AIAA Aerospace Sciences Meeting, Reno, NV, 11-14 Jan. 1999.
19) M. Y. Bahadori, U. Hegde and D. P. Stocker: 37th AIAA Aerospace Sciences Meeting, Reno, NV, 11-14 Jan. 1999.
20) M. Y. Bahadori, U. Hegde and D. P. Stocker: Fall Western States Meeting of the Combustion Institute, Irvine, CA, 25-26 Oct. 1999.
21) M.Y. Bahadori, U. Hegde and D. P. Stocker: 38th AIAA Aerospace Sciences Meeting, Reno, NV, 10-13 Jan. 2000.
22) U. Hegde, M. Y. Bahadori and D. P. Stocker: AIAA J., **38** (2000) 1219.
23) M. Y. Bahadori and U. Hegde: AIAA-2001-0621, 39th AIAA Aerospace Sciences Meeting, Reno, NV, 8-11 Jan. 2001.
24) A. Abbud-Madrid, F. K. Amon and J. T. McKinnon: 42nd AIAA Aerospace Sciences Meeting, Reno, NV, 5-8 Jan. 2004.
25) K. T. Dotson, P. B. Sunderland, Z.-G. Yuan and D. L. Urban: Eastern States Meeting of the Combustion Institute, College Park, MD, 18-21 Oct. 2009.
26) K. T. Dotson, P. B. Sunderland, Z.-G. Yuan and D. L. Urban: 48th AIAA Aerospace Sciences Meeting, Orlando, FL, 4-7 Jan. 2010.
27) K. T. Dotson, P. B. Sunderland, Z.-G. Yuan and D.L. Urban: 6th International Seminar on Fire and Explosion Hazards, Leeds, England, 11-16 April 2010.
28) K. T. Dotson, P. B. Sunderland, Z.-G. Yuan and D.L. Urban: Fire Saf. J., **46** (2011) 550.
29) B. Ma, S. Cao, D. Giassi, D. P. Stocker, F. Takahashi, B. A. V. Bennett, M. D. Smooke and M. B. Long: Proc. Combust. Inst., **35** (2015) 839.
30) S. Cao, B. Ma, B. A. V. Bennett, D. Giassi, D. P. Stocker, F. Takahashi, M. B. Long and M. D. Smooke: Proc. Combust. Inst., **35** (2015) 897.
31) D. Giassi, B. Liu and M. B. Long: Appl. Opt., **54** (2015) 4580.
32) D. Giassi, S. Cao, B. A. V. Bennett, D. P. Stocker, F. Takahashi, M. D. Smooke and M. B. Long: Combust. Flame, **167** (2016) 198.

33) T. F. O'Malley, W. A. Sheredy and D. P. Stocker: "Combustion Research on the International Space Station," Proc. 59th International Astronautical Congress, **2**, (2008) 756.
34) D. P. Stocker, F. Takahashi, J. M. Hickman and A. C. Suttles: Central States Meeting of the Combustion Institute, Tulsa, OK, 16–18 March 2014.
35) Advanced Combustion via Microgravity Experiments (ACME), https://www1.grc.nasa.gov/space/iss-research/iss-fcf/cir/acme/.
36) J. Tinajero, D. Giassi, D. P. Stocker and M. B. Long: 11th U.S. National Combustion Meeting of the Combustion Institute, Pasadena, CA, 24-27 March 2019.
37) J. Tinajero and M. B. Long: 12th U.S. National Combustion Meeting, 24-26 May 2021.
38) Y.-C. Chien, J. Tinajero, D. P. Stocker, U. Hegde and D. Dunn-Rankin: Central States Meeting of the Combustion Institute, Minneapolis, MN, 20-22 May 2018.
39) Y.-C. Chien, J. Tinajero, D. P. Stocker, U. Hegde and D. Dunn-Rankin: 11th U.S. National Combustion Meeting 2019, Pasadena, CA, 24-27 March 2019.
40) Y.-C. Chien, D. P. Stocker, U. Hegde and D. Dunn-Rankin: 12th Asia-Pacific Conference on Combustion Meeting, 1-5 July 2019, Fukuoka, Japan.
41) P. Dehghani, E. Auth, C. Cui, D. P. Stocker, J. L. de Ris, P. B. Sunderland and J. G. Quintiere: Eastern States Meeting of the Combustion Institute, Columbia, SC, 8-11 March 2020.
42) A. Snegirev, E. Kuznetsov, E. Markus, P. Dehghani and P. B. Sunderland: Proc. Combust. Inst., **38** (2021) 4815.
43) P. Dehghani, A. Wright, J. L. de Ris and P. B. Sunderland: 12th U.S. National Combustion Meeting, 24-26 May 2021.
44) P. Dehghani, P. B. Sunderland, J. G. Quintiere and J.L. de Ris: Combust. Flame, **228** (2021) 315.
45) P. Dehghani and J. G. Quintiere: Combust. Flame, **233** (2021) 111572.
46) P. H. Irace, H. J. Lee, K. Waddell, L. Tan, D. P. Stocker, P. B. Sunderland and R. L. Axelbaum: Combust. Flame, **229** (2021) 111373.
47) P. H. Irace, K. Waddell, Z. Xu, D. Constales, P. B. Sunderland, and R. L. Axelbaum: 12th U.S. National Combustion Meeting, 24-26 May 2021.
48) K. Waddell, P. B. Sunderland, S. Medvedev, S. Frolov, P. H. Irace and R. L. Axelbaum: 12th U.S. National Combustion Meeting, 24-26 May 2021.
49) Combustion Integrated Rack (CIR), https://www1.grc.nasa.gov/space/iss-research/iss-fcf/cir/.
50) V. Nayagam, D. L. Dietrich, P. V. Ferkul, M. C. Hicks and F. A. Williams: Combust. Flame, **159** (2012) 3583.
51) D. L. Dietrich, V. Nayagam, M. C. Hicks, P. V. Ferkul, F. L. Dryer, T. I. Farouk, B. D. Shaw, H. K. Suh, M. Y. Choi, Y. C. Liu, C. T. Avedisian and F. A. Williams: Microgravity Sci. Technol., **26** (2014) 65.
52) T. I. Farouk and F. L. Dryer: Combust. Flame, **161** (2014) 565.
53) G. Paczko, N. Peters, K. Seshadri and F. A. Williams: Combust. Theory Model., **18** (2014) 515.
54) V. Nayagam, D. L. Dietrich and F. A. Williams: AIAA J., **54** (2016) 1235.
55) D. L. Dietrich, R. Calabriab, P. Massolib, V. Nayagam and F. A. Williams: Combust. Sci. Technol., **189** (2017) 520.
56) P. B. Kuhn, B. Ma, B. C. Connelly, M. D. Smooke and M. B. Long: Proc. Combust. Inst., **33** (2011) 743.
57) B. Ma and M. B. Long: Proc. Combust. Inst., **34** (2013) 3531.
58) P. S. Greenberg and J. C. Ku: Combust. Flame, **108** (1997) 227.
59) P. S. Greenberg and J. C. Ku: Appl. Opt., **36** (1997) 5514.
60) Physical Sciences Informatics (PSI), https://www.nasa.gov/PSI.
61) Solid Fuel Ignition and Extinction (SoFIE), https://www1.grc.nasa.gov/space/iss-research/iss-fcf/cir/sofie/.