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Overview of the NASA Microgravity Combustion Program

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Recently, three major combustion experiments were carried out in the microgravity environment of the Space Shuttle on the Microgravity Science Laboratory-1 mission. These three efforts entailed a study of laminar soot processes in gaseous diffusion flames, a study of the structure of flame balls at low Lewis numbers, and a study of isolated droplet combustion. Descriptions of these three experiments and their preliminary results appear in the following three papers. The purpose of this paper is to "set the table" for these three papers through a discussion of the importance of microgravity to the study of fundamental combustion phenomena, a presentation of an overview of the current NASA microgravity combustion program, and a brief description (with references to more complete papers) of previous space-based microgravity combustion experiments carried out under the aegis of NASA.

Introduction

COMBUSTION is a major element of many critical technologies used by contemporary society. For example, electric power production, home heating, surface and air transportation, space propulsion, and many forms of materials processing and synthesis utilize combustion. Undoubtedly, as worldwide economic development accelerates, the role of combustion in production of heat and work and in other industrial activities will continue to expand. Although combustion technology is vital to our standard of living, it also poses great challenges to our environment. For example, production of pollutants, atmospheric change and global warming, unwanted fires and explosions, and the incineration of hazardous wastes are major current problems that would benefit from improved understanding of combustion. Thus, combustion phenomena influence our lives in many ways and have an unusually large impact on major societal needs facing us today. Major goals of microgravity combustion research include the development of better understanding, from a fundamental perspective, of the interactions between fluid dynamics, scalar transport, thermodynamics, and chemical kinetics inherent to combustion processes and the provision of predictive and design capabilities to enable and to enhance combustion energy utilization and fire safety. Specific potential practical benefits that may ensue in part from microgravity combustion research include 1) the reduction of combustion-generated effluents that pollute the atmosphere and contribute to global warming; 2) the reduction of fire and explosion hazards, which result in large losses in lives and property annually; 3) Improved hazardous waste incineration processes, leading to the alleviation of ever-increasing waste disposal problems; 4) increased efficiency of the conversion of chemical energy stored in fuels to useful heat and work in combustion devices, leading to a reduction in dissipation of scarce fuel reserves; and 5) the development of improved materials, via combustion synthesis, for use in widely diverse applications such as bone replacements, electrical components, and engines.

Rationale for Microgravity Combustion Studies

The effects of gravitational forces on Earth hamper combustion studies more than they impede most other areas of science. Combustion intrinsically involves production of high-temperature gases whose low densities trigger buoyant motion, vastly complicating the execution and interpretation of experiments. The effects of buoyancy are so ubiquitous that we often do not appreciate the enormous negative impact that they have had on the rational development of combustion science.[1] Perversely, the effects of buoyancy are strongest in the highest temperature regions of flames, where most of the chemical reactions occur. Buoyancy causes these reaction zones, where current understanding is most limited, to collapse into very thin sheet-like regions, not resolvable by existing or anticipated instrumentation, under normal gravity conditions. Buoyant motion also can trigger the onset of turbulence, yielding unsteadiness and small spatial turbulence scales as additional complications. Finally, buoyancy causes particles and drops to settle, inhibiting studies of heterogeneous flames important to furnace, incineration, and power generation technologies. Thus, the effects of buoyancy have seriously compromised our capabilities to carry out experiments needed to advance our understanding of flame phenomena. Microgravity offers potential for major gains in knowledge about combustion because it offers a unique capability for the experimentalist to establish the flow environment rather than having it dominated by uncontrollable (under normal gravity) buoyancy effects and, through this control, to extend the range of test conditions (e.g., low-speed flows, large droplet diameters, purely diffusive transport regimes) that can be studied. Thus, combustion scientists can use microgravity experiments to extend the range of variables examined while simplifying the study of many combustion processes. This allows precise examination of accepted, but unverified, theory and development of fresh insights into elemental phenomena also found in Earth-based combustion processes. These experiments also provide vital information concerning how fires behave in microgravity and how fire safety on spacecraft can be enhanced. Several examples of how microgravity can aid in studies of various combustion phenomena are outlined next.

Combustion–Turbulence Interactions

Virtually all practical combustion devices, except gas stoves, involve turbulent flows. The range of turbulence length and time scales—broadened greatly by buoyancy—generally precludes exact numerical simulation and also presents a significant challenge to experimental investigations. Microgravity uniquely limits the range of length and time scales to those large enough to be tractable experimentally and more readily simulated. Preliminary microgravity experiments have shown that buoyancy plays a role in the turbulence characteristics in jet diffusion flames where it had been previously assumed that the flowfield and flame behavior were independent of gravitational influence, e.g., at cold-flow Froude numbers greater than 1000 (Ref. 2). One particularly powerful computational approach for treating the coupling between fluid motion and

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combustion chemistry based on studies of laminar flames is currently under development worldwide; this approach, referred to as laminar flamelet theory, shows promise as a tractable representation of turbulent combustion. The extension of laminar flamelet theories to predict fully turbulent flames currently cannot be exploited, however, due to limitations caused by the interferences of buoyancy during laminar flame studies. Microgravity combustion studies provide an opportunity to eliminate these interferences and, thus, to markedly advance our capability to address turbulent combustion phenomena.

Transient Processes in Gaseous Flames

Numerous types of instabilities are possible in the combustion of gases, some of these being gravity dependent. Such phenomena as ignition, extinction, and unsteady response of flames to externally imposed perturbations, e.g., pressure oscillations, are also of major importance to fire safety, production of pollutants, and combustion efficiency. Research in a microgravity environment provides for the examination of fundamental phenomena involved in these transient phenomena without the confounding effects of buoyancy-induced flows that will, under normal gravity conditions, also respond in an unsteady manner to such imposed perturbations, often masking the phenomena of interest. With an understanding of these phenomena, strategies for controlling ignition, extinction, and responses of flames to externally imposed perturbations in practical combustion devices can better be devised.

Soot Processes

Soot is a critical element in many combustion systems, strongly affecting combustor lifetime, efficiency, peak power output, and pollution generation. The short timescales and small spatial volumes affecting soot formation and destruction processes under normal gravity conditions thwart experimental probing. Furthermore, buoyancy accelerates, in an uncontrolled fashion, the flowfield in which soot is formed and oxidized; this too inhibits scientific investigations. Microgravity experiments uniquely establish and control a low-speed flow environment and through this control extend the range of conditions involving soot processes that can be examined. The lack of buoyantly induced, accelerated flow results in longer residence times for primary soot formation, clustering, cluster-cluster agglomeration, and oxidation in a variety of flames.[3] In addition, soot particle pathlines are strongly altered under microgravity conditions, resulting in major changes in the environmental history seen by the soot precursors and particles. From the perspective of practical benefit, a fundamental understanding of the processes controlling soot formation, aggregation, and oxidation is of vital importance because such understanding would allow us to develop methods to predict and to control sooting associated with combustion processes under a wide variety of circumstances.

Droplet Combustion at Pressures up to Supercritical

Microgravity is of particular benefit in studies of liquid droplet ignition and combustion inasmuch as it eliminates settling effects and buoyancy-induced flows around the droplets, thus leading to truly symmetrical (and hence one-dimensional) geometry. Microgravity also allows a large isolated droplet to be retained within the field of view of various diagnostics. These features of microgravity experiments enable far more exact comparisons in terms of combustion times, extinction diameters, and flame standoff distances with early classical models (e.g., the models of Spalding[4] and Godsave[5]) and with more recent theories of isolated droplet combustion that treat effects of fuel vapor accumulation, nonunity Lewis numbers inside and outside the flame envelope, product absorption, liquid diffusion and circulation, low-speed gas flows, and radiative heat transfer.[6–11] Currently, high-pressure and supercritical fluid operation of combustion devices is being examined in a search for increased efficiency. Unfortunately, pollutant generation, e.g., soot and oxides of nitrogen, increases with increasing pressure; hence, military and NASA aeropropulsion research is heavily populated with studies aimed at simultaneous realization of the theoretical efficiency improvements and the minimization of pollutants. Another application of this technology is in the area of hazardous waste disposal: supercritical water oxidation of hazardous wastes has been predicted as an important technology of the future, which will yield, it is hoped, only benign products (carbon dioxide and water). Much of our detailed knowledge in the area of combustion of droplets and particles has been obtained at low pressure; an extension of studies to high pressure is required. For example, soot studies have mostly been performed at near-ambient pressures with flame temperatures of less than 2000 K; diesel engines operate at over 50 atm and 2800 K. Much of our knowledge of soot kinetics may not be applicable to these high-temperature, high-pressure regimes. High-pressure operation is accompanied by increased buoyant flow effects; microgravity experiments will enable, as in other situations, an isolation of the effects of buoyancy on flame structure, flammability, and flame speeds.

Classical Model Validation and Benchmark Data

Combustion textbooks are replete with theories that are incompletely tested though widely accepted (through historical precedent). These theories often neglect buoyancy effects and utilize simplified transport processes and/or assume one-dimensional behavior in situations where buoyant effects preclude it. Microgravity continues to offer the unique ability to test, via ideal, truly one-dimensional or axisymmetric experiments, the accuracy of specific aspects of theories and to provide a benchmark database against which extensions to existing theories and altogether new theories can be tested. Besides droplet combustion theory noted earlier, a quick scan of textbooks suggests the need for experimental data to truly validate fundamental models of gas jet diffusion flames, premixed gas flammability limits, isolated carbon or metallic particle combustion, and combustion of particle and droplet arrays.

Flame Structure and Elementary Mechanisms

A fruitful approach to achieving meaningful technology gains in combustion processes must be centered on the development of a better understanding of the fundamentals of the unit processes involved. Without such an understanding, the approach taken to improving combustion devices tends to involve incremental trial-and-error perturbations around current state-of-the-art designs, with opportunities to achieve possible major improvements with radically different approaches being missed. If one fully understands the physics and chemistry involved in a given combustion process, including detailed definition of the unit subprocesses and how they interact, this understanding can be combined into physically accurate models that can then be used for parametric exploration of new combustion domains via computer simulation, with the possible definition of radically different approaches to accomplish various combustion goals. Accordingly, emphasis should be placed on studies of combustion fundamentals that are not currently well understood; gravitational effects associated with normal Earth-bound combustion studies have prevented the study of many elementary processes that tend to be overshadowed by gravity-induced processes such as buoyancy or settling.

Direct Numerical Simulation and Large Eddy Simulation

Direct numerical simulation (DNS) and large eddy simulation are being widely pursued for definition of detailed features of flame structure and transport processes (and their interactions) associated with combustion. Because of the large range of length and timescales, DNS of practical or even idealized devices is considered to be a technology of the future, at best. DNS modeling to date, however, has shown the need to account for preferential mass diffusion even in turbulent flame environments. Microgravity experiments again lessen the range of scales and may make the problem tractable at least for model validation of laboratory-scale experiments, a first step toward DNS validation. DNS is expected ultimately to play a major role in the design of practical combustion systems and to obviate the need for the expensive construction and modification of a wide range of breadboards, prototypes, and experimental models of combustion devices; it may also be used for optimization of design elements, subsystems, controls, and overall system performance at reduced cost and time.

Spray and Aerosol Combustion

Spray and aerosol cloud combustion accounts for 25% of the world's energy use, and yet it remains poorly understood from both a fundamental and a practical perspective. Realistic sprays include a liquid breakup region, dispersed multiphase flow, turbulent mixing processes, and various levels of flame interactions through the spray. Idealization of spray configurations in a quiescent environment (the starting point for models) has been impossible in 1 g due to the settling of large droplets and buoyant pluming of postcombustion gases. Microgravity offers the promise of such idealization but has just begun to provide experimental data on ignition and on flame-front spreading as affected by interactions between droplets in idealized linear and planar arrays of monosized droplets. Improved understanding of the flammability and flame interactions of sprays can be expected to yield improved combustion efficiency in practical devices; this will only occur with an improved detailed theoretical description. In the area of combustion safety, dust clouds contribute to accidental fires and explosions, e.g., grain elevators and underground mines. Finally, improved spray technology can be applied to improvements in hazardous waste incineration.

Combustion Synthesis

The use of flames to synthesize materials is expanding rapidly. Products include valuable vapors (e.g., acetylene), ultrafine particles (fullerenes, silicon oxides, and titanium oxides), coatings (diamonds), and monolithic solids (boron carbide and titanium boride). Fullerene production is being investigated extensively, but the product yields of fullerenes are currently typically less than 1%, leaving tremendous potential for improvement. Sedimentation and buoyant plumes, which lead to limited critical residence times, again interfere with investigations into the scientific mechanisms of material production and the improvement of the quality of the actual industrial product. For example, pressure and buoyancy effects on soot-filled flames are not understood sufficiently to determine the ideal operating conditions to maximize fullerene generation in either premixed or diffusion flames. Microgravity offers the promise of isolating the effects of pressure by removing the influence of buoyancy on the material production process. A major difficulty in self-propagating, high-temperature synthesis (SHS) of materials is the control of porosity and the microstructure of the products. SHS reactions generating gaseous, liquid, or combined phases are prone to gravity-induced fluid flows, leading to nonuniform microstructure and undesirable properties of the product material due to segregation and density gradient effects. Gravitational forces have been shown to play a dominant role in controlling both the combustion-synthesis reactions and the morphologies of the synthesis products. Current research is geared towards interpreting the differences between normal- and low-gravity processing.

Surface Flame Spread

Anyone who has observed the combustion of solid fuels, particularly flame spread up vertical walls, is well aware of the dominant effects of buoyancy on such processes under normal gravity conditions, a dominance that makes the understanding of other phenomena involved very difficult (an example of how buoyancy can mask such phenomena). Accordingly, microgravity studies of flame spread across solid fuels (and liquid pools) are of considerable interest from a fundamental point of view as well as being very important in terms of fire safety on various space platforms. On Earth, the fluid mechanics of large-scale fires are complicated by buoyancy-fed turbulent processes and thermal radiative interactions with surrounding materials, terrain, and building structure. Current models are still somewhat primitive, with little elucidation of the role of thermal radiation in almost any aspect of fires. In fact, this area, though of considerable practical importance, is generally omitted from textbooks because of these weaknesses in understanding. Investigations of large-scale fires under microgravity conditions have yet to begin, but it has been shown that radiation takes on heightened importance in small-scale fires in microgravity, indicating that results from laboratory-scale experiments in microgravity might be utilized in modeling large-scale fires. In terms of NASA's own direct interests, ongoing investigations of material flammability and fire behavior in microgravity have yielded vital guidance to improved fire safety aboard orbiting spacecraft.

NASA's Microgravity Combustion Program

Currently, NASA's microgravity combustion science program is supporting approximately 50 ground-based studies (including experimental studies utilizing drop-tower facilities and/or parabolic aircraft, along with analytical modeling efforts) and 18 projects that are utilizing or are expected to utilize extended duration testing in microgravity afforded by space-based experiments on sounding rockets or orbiting facilities (the Space Shuttle or a space station). These studies can be divided into seven major categories: premixed gas flames; gaseous diffusion flames; combustion of individual fuel droplets, clusters of droplets, and sprays; combustion of individual solid particles and dust clouds; flame spread across liquid and solid fuel surfaces; smoldering combustion; and combustion synthesis. In addition, a number of advanced diagnostic instrumentation technologies are being developed for experimental microgravity studies, especially in the space environment, under severe constraints as regards volume, mass, and power.

In the area of premixed gas flames, NASA is currently supporting experimental and modeling studies of the effects of gravity on flammability limits,[12–18] flame stability/extinction,[19,20] flame structure and shape,[21–23] and sooting.[24] In particular, studies of the effects of radiative heat losses on premixed flames in microgravity environments (where such effects dominate flammability limits) and near-limit flame structure/behavior are being funded. Modeling activities being supported include both simplified analytical approaches aimed at elucidating mechanisms and detailed numerical analysis aimed at quantifying them. In addition, NASA is funding microgravity studies of low-flow premixed turbulent flames, which cannot be studied in normal gravity environments due to strong buoyancy-induced flows. From such studies, researchers hope to resolve effects of buoyant convection on flammability limits and to define mechanisms that control flammability limits and that contribute to flame stability and shape, with a final output being an increased understanding of fundamental flame properties and a rigorous testing of theoretical models, both important to improvements in combustor design and fire/explosion avoidance. To date, several discoveries, possible only via microgravity experiments, have been made in this area; these include self-extinguishing flames, flame balls, flame cylinders, and dilution-enhanced flammability,[25] all important to hazard control and basic combustion science.

Activities being supported in the area of gaseous diffusion flames include the study of the effects of diffusion-flame structure (quite different in normal gravity and microgravity) on soot formation; the effects of altered relationships between chemical kinetic timescales and flow timescales accompanying a change from normal gravity to microgravity on such parameters as smoke-emission limits, ignition and stability limits, and burning rates; and the effects of buoyancy on the structure of gas-jet diffusion flames in laminar, transition, and turbulent flow regimes. In particular, chemical kinetics and species/heat transport tend to be closely coupled in diffusion flames, leading to difficulty in separating and thus quantifying their individual contributions; use of microgravity experiments provides a means of altering the balance between these processes, thus permitting isolation of the individual mechanisms. Within this category, the first data on turbulent and transition gas-jet flames in microgravity have recently been obtained,[26–28] offering potential toward the development of an understanding and a prediction of turbulent combustion phenomena of widespread practical interest. In addition, phenomenological data on soot production in microgravity flames are being obtained for use in developing soot kinetics models, with eventual application to the development of effective strategies for control of soot formation in practical burners. These studies are expected to have significant impact on understanding and predictive capabilities as regards diffusion flames, ultimately leading to approaches for achieving a significant reduction of pollution and increased energy conversion efficiencies in devices utilizing such flames.

In the area of droplet combustion, NASA supports fundamental studies of microgravity combustion of isolated, single-component,[6,10,29–31] and multicomponent truly spherical droplets.[32–34] In addition, we are supporting studies of the combustion of ordered arrays of fuel droplets in a microgravity environment,[35–37] of droplet clusters,[38] and of sprays produced by an electrostatic dispersion process,[39,40] to develop an understanding of the interactions of combustion of individual droplets in spray combustion (used in many practical combustors). To date, several new phenomena related to droplet combustion have been revealed in drop-tower testing, including disruptive burning of initially single-component droplets, wider oxygen limits, soot-shell formation (under conditions where no soot forms in 1-*g* testing), and radiative extinction at large droplet diameter. From these studies, we hope researchers will develop greatly improved understanding of spray combustion processes, leading to major improvements in the design of combustors utilizing liquid fuels.

Another combustion area of major importance, particularly in terms of fire safety, is flame propagation in fuel-dust clouds; it is particularly difficult to study ignition and combustion characteristics of such clouds in a normal gravity field due to the tendency of an initially well-dispersed dust cloud to quickly settle in such a field. This can lead to the coalescence of particles, which collide during this settling process, and to nonuniform air/fuel ratios within the cloud before ignition. In addition, buoyant flow induced by combustion creates uncontrollable nonuniformities. Accordingly, microgravity provides essentially the only means of studying the fundamentals of dust cloud ignition and combustion. Microgravity experiments showing "chattering flame propagation" in freely suspended fuel particle clouds have led to theoretical developments regarding flame-acoustic interactions that apply to the triggering of acoustic instabilities in practical gas turbines. At this time, NASA is funding a study of the detailed mechanisms of ignition and the combustion of individual solid particles, a study of the combustion of porous solid fuel particles, a study of the interactions of burning metal particles, and a study of the structure and dynamics of reacting dusty flows.[41–44]

Currently, NASA is supporting several experimental and analytical studies of the spread of flames across solid and liquid fuel surfaces, both in quiescent oxidizer environments and with low-velocity flows both in the same direction and opposed to the flame spread direction.[45–57] The immediate goals of these activities are to develop a better understanding of what controls ignitability of solid or liquid fuels in various oxidizer environments, what physical processes control fire spread, how flames propagate and grow, what inhibits the burning of solid fuels, and what conditions lead to extinction. Benefits from the development of a better understanding of the fundamental processes controlling flame spread over solid or liquid fuels lie mainly in the area of fire safety.

Another combustion process of importance to fire safety is smoldering combustion, a relatively slow nonflaming exothermic oxidation process involving a gaseous oxidizer and a porous solid fuel, well exemplified by the combustion of a cigarette. At this time, NASA is supporting two programs in this area,[58,59] one an experimental study of the mechanisms of smoldering combustion in polyurethane foam and the other an analytical modeling effort of smoldering in general. The long times required for experiments of this nature require flight experiments for the definition of microgravity effects; these experiments are being used in conjunction with ongoing ground-based normal-gravity experiments to develop a better understanding of the fundamental mechanisms of smoldering combustion, which should have a significant impact on the prevention of unwanted fires both on the ground and in space.

In the area of self-propagating, high-temperature synthesis of materials, NASA is supporting a study in which an exothermic combustion reaction is being used to produce a porous ceramic-ceramic matrix that is infiltrated with the excess reactant metal.[60] A major goal of this study is the definition of fundamental mechanistic differences between how this combustion synthesis reaction behaves under normal- and low-gravity conditions, with the ultimate aim of defining approaches to tailoring combustion synthesis processes for the production of materials with optimized properties for various end uses. Also in the area of combustion synthesis, NASA has recently initiated funding of a study of the effects of gravity on combustion synthesis of fullerenes[61] and another study on the production of metal and ceramic nanoparticles.[62]

To date, ground-based work in microgravity combustion has demonstrated major differences in the structures of various types of flames from those seen in normal gravity. Besides the practical implications of these results to combustion efficiency (energy conservation), pollutant control (environmental considerations), and flammability (fire safety), these studies establish that better mechanistic understanding of individual processes making up the overall combustion process can be obtained by comparing results gathered in microgravity and in normal-gravity tests, with the potential for major improvements in the design of combustion processes and hardware for use on Earth as well as in space.

Earlier NASA Space Combustion Experiments

The following paragaphs discuss only those combustion experiments that were performed in space before the recent Microgravity Science Laboratory-1 (MSL-1) flights: experiments conducted on MSL-1 are described in detail in the following three papers. Although the MSL-1 mission carried by far the most extensive set of space combustion experiments to date, considerable earlier space experimentation aimed at determining the effects of microgravity on combustion processes has been carried out: Included are experiments on candle flames, combustion of fuel droplets positioned on support fibers, ignition and spread of flames across solid fuel surfaces, flame spread across liquid fuel pools, smoldering combustion, and production of soot in flames as related to fire detection.

Many other tests on combustion systems have been performed in microgravity in drop towers and aircraft.[‡]

Candle Flames

The most frequently asked question regarding microgravity combustion is if and how a candle flame might burn in a weightless environment. Accordingly, the candle flame was used to demonstrate the pivotal role gravity plays in simple combustion systems. The experiments conducted addressed the characteristics and survivability of a classical diffusion flame in quiescent air in microgravity; these experiments were flown initially on the Space Shuttle and then, with some modifications, on the *Mir* Space Station.[63,64]

About 10 single-candle flame tests were run in the Space Shuttle inside a perforated candlebox that was in turn placed inside a small, sealed work volume known as the glovebox facility. Immediately after ignition, the candle flame was spherical with a bright yellow core. After 8–10 s, the yellow glow, presumably from soot, disappeared, and the flame became blue and hemispherical. These behaviors are consistent with earlier, Earth-based short-duration studies in low gravity. After the ignition transient, the flames remained blue and free of soot with a diameter of approximately 1.5 cm. The transport rates were driven by diffusion alone and were therefore much smaller than the rates on Earth, which are driven by both buoyant convection and diffusion. As a result, the ratio of heat generation to heat loss from the flame became smaller. This caused the flame temperature to be lowered to the point that little or no soot formed, as evidenced by the all-blue flame. It also caused the flame to anchor far from the wick, so that the burning rate, i.e., the amount of wax consumed per unit time, was reduced.

Extinction generally occurred between 40 and 60 s after ignition. The cause of extinction in the Space Shuttle experiments was believed to be oxygen depletion in the finite volume of the glovebox/candlebox. To test this possibility, over 75 tests were performed on *Mir* with a more open candlebox and a larger glovebox volume. These candle flames survived for up to 45 min in a slightly enriched oxygen environment (the measured oxygen concentration on *Mir* at the time of these experiments was 23–25%), confirming the existence of a quasisteady behavior for the candle flame.

In both the Space Shuttle and *Mir* experiments, each candle flame oscillated spontaneously for about 5 s before extinction, with the flame symmetrically tracing back and forth along the candle axis in each cycle. The oscillations had a frequency of about 1 Hz with an initially small amplitude that continuously grew until extinction. These oscillations have become the subject of subsequent theoretical efforts.

Fiber-Supported Droplet Combustion

Although the candle flame represents one type of stationary flame that can be uniquely studied in combustion, it is recognized as being

[‡]A complete bibliography associated with these tests may be found on the Internet at <http://www.lerc.nasa.gov/Other_Groups/MCFEP>.

quite distant from practical applications. The fiber-supported droplet combustion (FSDC) experiment, although still motivated by scientific concerns, involves realistic fuels used in a variety of applications, including internal combustion engines and jet engines. The theory developed in the 1950s to predict droplet burning rates assumed, among other things, spherical symmetry, quasisteady behavior (gas-phase processes that were fast relative to the rate of droplet consumption), and droplet temperature equal to its boiling temperature. The resulting model predicts that the square of the droplet diameter decreases linearly with time[4,5] and that the ratio of flame diameter to droplet diameter is a constant throughout the droplet lifetime. More advanced models relax many assumptions (but not the assumption of spherical symmetry) and may more accurately predict behavior in both the liquid and gas phases.[8,9,65,66] Unfortunately, in normal-gravity experiments, buoyancy destroys spherical symmetry by inducing convective mixing in the gas and liquid phases; thus, low-gravity experiments provide the best test of these advanced models. In the FSDC experiment, fuel droplets of various sizes and compositions were tested under a variety of conditions for the following purposes: 1) methanol droplet combustion in quiescent air, to examine the effect of initial droplet size on the transient burning rates and to observe the flame extinction process; 2) methanol droplet combustion in a slow convective flow, to study the effect of a slow, uniform airflow on flame shape and burning rates; 3) n-heptane/hexadecane miscible binary-fuel droplet burning, to study the effects of fuel mixture volatility on the transient burning histories, flame behavior (especially the sudden contraction of the flame caused by the rapid buildup of hexadecane at the liquid surface), and soot dynamics; 4) methanol/dodecanol miscible binary-fuel droplet combustion, to study the same effects as 3, except that because this fuel mixture burns without soot, the results can be compared with existing simplified theories; and 5) methanol/water mixture droplet combustion, to study the effect of water dissolution on the burning characteristics of alcohol fuels.

Thirty-nine droplet tests were run in air at 300 K, with most of them yielding publishable data. The droplets were tethered to a thin-diameter fiber, and the flame and droplet images were recorded by a video camera. A computer-based image analysis system was used after the flight to obtain droplet diameter-vs-time and flame-diameter-vs-time data. Initial droplet sizes ranged from 2 to 5 mm: the extinction diameter increased, as expected, with this parameter. The extinction diameter of the largest droplet was 2.5–3 mm; this size at extinction is larger than that at which experimentalists begin to burn droplets on the ground. In the case of the alcohol-containing fuels, the remaining droplet was mostly water. The data obtained allowed the first comparison of theoretical predictions for droplets of this size to experimental observations, with the observed burning rates generally being smaller than predicted by theory.

In several tests, a low-speed airflow was started after the droplet was ignited. This sharply increased the flame luminosity and changed the flame shape from spherical to ellipsoidal, as expected. These data are being compared with a numerical model in development. Finally, a few tests were run with different fiber diameters (80 and 140 μm) to study the effect of fibers on the combustion processes.

As indicated earlier, several series of tests were conducted with fuel mixtures. In the first series, the initial water content in methanol fuel droplets was 10 and 20% by mass. These tests showed that the burning rate diminished and the extinction diameter increased with increased water content, in qualitative agreement with predictions. Next a series of tests with sooting fuel mixtures (e.g., heptane + hexadecane with hexadecane mass fractions of 0.1–0.4) was run. For a droplet of about 3-mm initial diameter, three-stage burning occurred, consistent with drop-tower testing on smaller droplets. A droplet of about 5-mm diam, however, showed unexpected results in that the burning rate continuously decreased during combustion, and an amount of soot far more than expected was issued, passing through the flame surface without being fully oxidized. Most subsequent testing was done with smaller droplets to lessen the amount of soot produced. These tests revealed the existence of very large aggregates of soot surrounding the droplet. Finally, the methanol/dodecanol droplets (initial dodecanol mass fractions of 0.2 and 0.4) exhibited disruptive burning. In some cases, interpretation was complicated by bubbles present initially in the liquid.

This set of experiments demonstrated that fuel droplets as large as 5 mm in diameter burned largely as predicted by droplet theory and by extrapolations of the experimental data with smaller droplets. Qualitative agreement was found between the theoretical and numerical predictions and the experimental data on extinction diameters for methanol and methanol-water mixtures; agreement between the numerical model and the experimental data has been shown to be improved when radiative heat loss from the flame is included in the model.

Ignition and Flame Spread Across Solid Fuel Samples

A series of projects involving solid fuel combustion have been performed on the Space Shuttle and on *Mir*. These experiments focused on the determination of the effects on ignition and flame spread in microgravity of the following initial conditions: oxygen concentration, ambient pressure, radiant heat flux, gas flow speed and direction, ignition source type and location, fuel type, fuel thickness, and fuel sample temperatures.

Solid Surface Combustion Experiments

The Solid Surface Combustion Experiment (SSCE), begun in space in late 1990, were the first combustion experiments performed on the Space Shuttle and the first in space since those done in 1975 in Skylab. The SSCE consisted originally of a series of eight tests of flame spread across solid fuel surfaces, five using ashless filter paper thin sheets and three using polymethylmethacrylate (PMMA) thick sheets, also known as Plexiglas®. These materials were selected for testing because an extensive normal-gravity database already existed with which comparisons could be made. Each test was conducted in a quiescent atmosphere of oxygen and nitrogen, and the oxygen mole fraction ranged from 0.35 to 0.70.

The results of the original eight flight tests were summarized in a series of papers by the investigators, from which these comments are paraphrased.[46,47,67–69] The flames all elongated during spread. The spread rate for the paper samples became steady almost immediately after ignition. Trailing surface reactions were noted, indicating that the fuel was not completely pyrolyzed after the flame passed. As anticipated, the spread rate for the thin paper samples increased with increasing ambient oxygen mole fraction. The spread rate also increased with ambient pressure, a finding not predicted unless radiative heat transfer effects, generally negligible in normal-gravity experiments of this kind, are included. These experiments also showed that the brightness of the flame and the visible soot radiation increase monotonically from the slowest to the fastest spreading flame. Steady-state theory compared well with experiments in the vicinity of the flame leading edge. The trailing flame structure can only be captured, however, with unsteady models of flame spread.

For the thick PMMA tests, the flame spread across the full length of the fuel samples, but the spread rate slowly decreased with time. Modeling indicated that the flame would eventually self-extinguish in a quiescent environment even at relatively high oxygen concentrations due to the time-dependent oxygen gradient near the flame front becoming weaker and weaker, providing less and less oxygen to the spreading flame. When combined with radiative heat losses and heating into the depth of the solid (the heated layer in the solid was observed to increase with time), the flame eventually becomes too weak to survive. The difference between the survivability and spread rate character of the thin and thick fuel samples suggests that there is a critical fuel thickness above which a flame will not survive in quiescent environments in microgravity.

Radiative Ignition and Transition to Spread Investigation

The next solid fuel flame spread project, the Radiative Ignition and Transition to Spread Investigation (RITSI), studied the ignition process and the transition from this initial ignition to a fire spread situation.[57,70] Samples in two-dimensional and three-dimensional configurations were heated and ignited by a radiative heat source, with subsequent transition to flame spread, in the presence of very low speed airflows. These tests utilized ignition at the middle rather than the end of the fuel samples. In the two-dimensional tests, the ignition stimulus was applied across the full width of the fuel sample to initiate planar two-dimensional spread in the axial direction. In the three-dimensional tests, ignition was limited to a central spot, allowing spread to occur in all directions. The key feature of this ignition approach is that a flame may spread simultaneously both upstream and downstream or may split into two or more flames that propagate at different rates and extinguish at different times. The airstream, however, comes principally from one direction, at magnitudes from 1 to 15 cm/s.

A total of 25 tests were conducted with ashless filter paper. Radiative ignition by a heating lamp followed by successful transition to flame spread occurred in all experiments except at zero imposed flow velocity. This has never been observed at normal gravity with this hardware; i.e., ignition in 1 *g* always needed assistance by a hot-wire ignitor near the fuel surface. This finding indicates that the transition to full combustion tends to be easier in microgravity than in normal gravity for this system. Completely opposite to observations in normal gravity, the flame spreads preferentially upstream when only a very low speed forced airflow is provided. When the paper sample is unconfined on an edge, the flame spreads much faster at this edge than it does along the center of the sample. In general, the flame spreads much faster in the three-dimensional configuration than it does in the two-dimensional configuration.

Wire Insulation Flammability

The Wire Insulation Flammability experiment was designed to simulate the heating of electrical wiring and the properties of burning wire insulation in a microgravity environment.[71] Wires coated with polyethylene insulation (realistic insulation materials were later studied, as discussed later) were heated at different rates by passing different amounts of electrical current through them. When the wire insulation reached a predetermined temperature, a crew member deactivated the current flow and triggered an ignitor to initiate a flame. Images of the temperature displays and the spreading flame were recorded on a video camera for later analysis. While the flame was spreading, a vacuum bottle was opened to obtain a sample of the combustion products.

Only four tests were run initially, but these provided several unique observations. As the flame propagated in a concurrent airflow, an excess of upstream solid fuel melted. This molten fuel accumulated, forming a growing, quasispherical bead two to three times the initial diameter of the insulation, not always symmetric with respect to the wire. The surface of the fuel near the flame was discolored and opaque, perhaps due to oxidative degradation of the polyethylene; this discoloration does not occur in normal-gravity heating tests conducted in a nitrogen environment. In one test, ignition was attempted without airflow. A torroidal cloud of vapor or condensed pyrolysis products formed around the igniter and a flame burned weakly in quiescent air but ultimately failed to propagate. In the final test of this series, the airflow was switched off after the flame reached the end of the sample. The flame quenched rapidly, leaving a nearly spherical fuel bead, 4–5 mm in diameter. This result provides a dramatic demonstration of the effect of low-speed flow on the flammability of materials in microgravity. These initial four tests were conducted at approximately 10 cm/s flow velocity, resulting in flames with an open downstream tip from which long strands of soot agglomerates were emitted. In low-speed flows (1–5 cm/s) observed in later experiments on the *Mir*,[72] the downstream flame tips were closed, and the flame nearly spherical. In all cases the rate at which the fuel melted exceeded the vaporization rate such that a growing fuel droplet accumulated inside the enveloping flame. This effect was more pronounced at the lower flow velocities.

Forced Flow Flame Spread Test

The Forced Flow Flame Spread Test[73] provided further observations of flame spreading over initially solid fuels in the presence of very low speed airflows (1–10 cm/s). The authors summarized their experimental conditions as follows. Three types of 13-cm-long samples were tested: flat cellulose wafers, 5 cm wide, ranging in area density from 1 to 41 mg/cm^2 (half-thickness) ignited in varying concurrent flow velocities; cylindrical cellulose cast on a heater core ignited at initial temperatures from 75 to 125°C in varying concurrent flow velocities; and polyethylene wire insulation samples heated to 100°C ignited in both concurrent and opposed flow configurations at different flow velocities.

The flame length spreading over the thinnest flat cellulose sample shrank during burning, suggesting a preheating of the downstream fuel by the ignitor. The flame over the thickest sample grew continuously during the test, though it grew more slowly near the end of the test. At a concurrent flow velocity of 1 cm/s, a sample of intermediate thickness approached a steady flame length similar in shape and size to that of the numerical predictions, but just near the end of the test where little downstream fuel remained. Hence the influence of limited sample length was apparent in each case. If a steady, constant flame length concurrent flow flame spread is to be observed, longer samples are required.

The effects of both concurrent flow velocity and initial fuel temperature on flame length were observed for the cylindrical cellulose samples. At a concurrent flow velocity of approximately 2 cm/s and a fuel preheat temperature of 100°C, the flame reached a steady length within 45 s of the recorded 90 s of burning. At a lower temperature, the flame was slowly shrinking at the end of the test. At higher temperatures and higher flow velocities, the flames were growing throughout the test time.

These tests provide support for the theoretical predictions of steady flame growth in low-speed concurrent flows. That theory predicts that the downstream heating of fuel by convection and radiation, an accelerating process in high-speed flows, is sufficiently tempered at low flow velocities by radiative losses from the flame and the fuel surface to permit an equilibrium flame.

Diffusive and Radiative Transport in Fires

The final set of experiments conducted to date in space in the area of flame spread across solid samples was entitled Diffusive and Radiative Transport in Fires (DARTFire).[53] This series, building upon the SSCE PMMA results, investigated flame initiation, flame spread, and postspread steady-state combustion of a thick solid fuel sample under various very low speed oxidizer flows (1–15 cm/s velocities). The very low speed gas flow was intentionally of the same order as the flame spread rate or fuel blowing velocity, i.e., vaporization rate, to better delineate those diffusive and radiative aspects of the problem that must be included in flame spread theories. Because radiant heat loss can lead to flame extinction, small amounts of radiant heating were imposed on the fuel sample; this enabled the flame to survive and spread under flow/composition conditions where it otherwise would have extinguished.

Ignition and Flame Spread Across Liquid Pools

A pool of n-butanol in air was ignited to determine the flame spread character in the presence of forced airflow. These experiments were conducted in a sounding rocket because of the hazardous nature of the experiment and to enable the use of extensive diagnostics.[55,74] Even with forced air velocities of the same order of magnitude as that induced naturally by buoyancy in normal gravity, the microgravity flame behavior was found to be completely different. Whereas the 1-*g* flames were soot producing and pulsated and spread rapidly, the microgravity flames were free of soot and spread steadily and very slowly. Rainbow schlieren measurements showed that heat penetrates far deeper into the pool in microgravity, suggesting that the major effect of liquid-phase buoyancy is its stratification of the temperature field under normal-gravity conditions; its absence in microgravity may lead to a very different liquid-phase surface temperature, flowfield, and flame spread character. Infrared thermography revealed heretofore unobserved liquid surface temperature and side flow phenomena in both 1 *g* and microgravity. Particle image velocimetry was used for the first time to obtain quantitative, full-field liquid-phase velocity fields ahead of the flame, revealing significantly more surface flow in microgravity than in 1 *g*. A state-of-the-art model's predictions were qualitatively confirmed in regard to gravitational effects on flame shape, flame extinction in microgravity when there is no opposed airflow, and fuel consumption rate. Disagreement was found in the flame spread character in microgravity, unless hot gas expansion was artificially set to zero in the model.

Smoldering Combustion

Two sets of experiments directed entirely at the smoldering combustion process have been conducted. The first set of such experiments were from the Smoldering Combustion in Microgravity (SCM) project,[75–77] with the principal SCM test variables being the ignitor geometry and the convective environment. Through the use of an axial ignitor and a plate ignitor, both radial and axial smolder propagation through polyurethane foam were investigated. For each ignitor geometry, one test was conducted with a quiescent environment and one with a low-velocity flow, resulting in a total of four test conditions. In no case was smolder sustained in a quiescent environment, or even with a slow forced airflow, due to conductive heat losses from the sample. While the igniter was powered, the material thermally degraded, however, and produced carbon monoxide at a level up to 300 times that observed in similar experiments on Earth.

The second set of smoldering experiments, following SCM, were from the Microgravity Smoldering Combustion (MSC)[78] project conducted on two Space Shuttle flights. The conditions for the first set of tests were quiescent environment with 35% oxygen/65% nitrogen and opposed airflow with 1-mm/s velocity. For the second set, they were still environment with 40% oxygen/60% nitrogen and opposed airflow with 2-mm/s velocity. MSC experiments were performed in a 20-liter, semicylindrical, hermetically sealed, aluminum combustion chamber. Polyurethane foam was again selected because it is representative of materials commonly used both on Earth and in space-based facilities. On both flights, the forced flow samples showed complete smolder front propagation. Neither of the quiescent cases, however, propagated. This is a dramatic difference from normal-gravity smolder, where the smolder reaction propagates vigorously along the whole sample length for both of these nominally quiescent conditions. Both tests with a forced flow, on the other hand, showed strong smolder propagation along the whole length of the sample. The magnitude of the microgravity smolder spread rate was between the corresponding upward and downward 1-*g* smolder spread rates. Gas analyses from these experiments did not show excessive CO production in microgravity; the difference in the SCM and MSC results is attributed to sample size and environmental conditions.

In addition to the two dedicated experiments just described, four novel smoldering tests were conducted as part of the RITSI experiment (described earlier) with ignition initiated by the lamp. Although a ring-shaped smoldering front was observed in normal gravity, unexpected, very complex peninsula-shaped char with smoldering fronts at the peninsula tips was observed under microgravity conditions. A theory is being developed to explain these observations.

Comparative Soot Diagnostics

The final experiment to be discussed here has significant practical application to NASA's mission. NASA uses smoke detectors on the Space Shuttle and the International Space Station to signal the presence of a fire event. Their design and in particular their alarm criteria, however, are based entirely upon 1-*g* data. Drop-tower experiments with very rapidly overheated wire showed that larger particles and aggregates occur in microgravity as compared with 1 *g*, raising questions about alarm setpoints.[79,80] As part of the Comparative Soot Diagnostics experiments, the detector systems were tested to determine their response to sources of particulate generated under long-duration smolder/combustion conditions in low gravity. The particulate sources included a candle tested at three coflow air velocities and four overheated materials (paper, silicone rubber, and wires coated with Teflon® or Kapton®), each tested at three heating rates. The coflow of air in these candle tests produced prodigious amounts of soot and ready emission of smoke, unlike the previous tests with candle flames that were free of soot because the air was quiescent. Soot aggregates collected via thermophoretic sampling suggested that the size of the aggregates was different than in 1 *g*, but not to the extent found in the previous short-duration tests. The pyrolyzed Teflon and Kapton yielded a liquid product that was difficult to collect for analysis. Both detectors responded to the smoke from all of these sources in preflight normal-gravity tests. In flight tests, a key conclusion, however, was that the response of a detector to a material burning in normal gravity is not a good indicator of the detector's ability to respond to the same material burning in microgravity.

Conclusion

This paper has presented an overview of the NASA microgravity combustion science program and a brief description of those microgravity combustion experiments conducted in space before the flight of MSL-1. These experiments have been accompanied by numerous other microgravity experiments—providing thousands of test points—performed in the last decade in ground-based facilities such as drop towers and low-gravity aircraft in the United States, Europe, Russia, and Japan. These experiments have already provided many insights into combustion processes. As delineated in the following papers, MSL-1 has provided a vast jump in the expansion of understanding of combustion processes. Further missions on the Space Shuttle and eventually on the International Space Station are planned, with the goals of the development of knowledge of combustion processes that will enable us to rewrite the textbooks and the provision of significant increases in the conversion of fuel energy to useful work, significant decreases in combustion-generated pollution, and improved fire safety.

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