

NASA Technical Memorandum 103189

New Findings and Instrumentation from the NASA Lewis Microgravity Facilities

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(NASA-TM-103189) NEW FINDINGS AND
INSTRUMENTATION FROM THE NASA LEWIS
MICROGRAVITY FACILITIES (NASA) 8 DCSC 22A

WFO-26163

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63/29 0295230

Prepared for the
Second Workshop on Microgravity Experimentation
sponsored by the National Research Council—Canada
Ottawa, Canada, May 8-9, 1990

NASA



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Several portions of this document are taken verbatim from NASA TM-101424. Although some changes or additions have been made, the contributions of the following people are gratefully acknowledged: Dan Gotti (Instrumentation), John Haggard (Droplet Combustion), and Prof. Paul Ronney (Premixed Gas).

INTRODUCTION

The study of fundamental combustion and fluid physics in a microgravity environment is a relatively new scientific endeavor. The microgravity environment enables a new range of experiments to be performed since: (a) buoyancy-induced flows are nearly eliminated; (b) normally obscured forces and flows may be isolated; (c) gravitational settling or sedimentation is nearly eliminated; and (d) larger time or length scales in experiments become permissible. As will be discussed, unexpected phenomena have been observed, with surprising frequency, in microgravity experiments, raising questions about the degree of accuracy and completeness of our classical understanding.

The purpose of this paper is to provide an overview of some new phenomena found through ground-based, microgravity research, the instrumentation used in this research, and plans for new instrumentation.

MICROGRAVITY COMBUSTION SCIENCE EXPERIMENTS

In the following sections, a sampling of microgravity combustion experiments, accomplished in drop towers or aircraft, is provided. A more complete list may be found in NASA TM-101424; herein highlights are for only those projects which resulted in

the discovery of previously unseen, combustion phenomena.

PREMIXED GAS COMBUSTION: Gravity affects premixed gas flames through buoyancy-driven convection. This effect is generally small except in mixtures with low burning velocities. In most fuel-air mixtures burning in normal gravity, this condition corresponds to mixture compositions far from stoichiometric. When the mixture is sufficiently fuel-lean or fuel-rich, buoyancy effects become apparent. For example, a sufficiently fuel-lean mixture may yield a flame which propagates only upward in normal gravity. In microgravity, ignited by a spark in the center of a constant volume pressure vessel, flames propagate in a slow, spherical fashion due to the reduction of buoyancy.

The limiting mixture compositions (e.g. most fuel-lean, most fuel-rich, or most diluted) which can sustain flame propagation are called flammability limits. Despite decades of study, the mechanisms of flammability limits are not well understood. Previous investigations in normal gravity suggested that buoyant convection is the dominant contributor to these mechanisms. Recent microgravity studies, both theoretical and experimental, verified this suggestion, finding wider limits in microgravity than occur in upward propagating flames in normal gravity. Furthermore, the characteristics of these

limits were very different from those observed in normal gravity. As opposed to buoyancy-caused limits in normal gravity, radiative heat losses from the hot combustion gases are often the primary factor leading to flame extinguishment in microgravity.

A new mode of unstable flame propagation, called Self-Extinguishing Flames, or SEFs, was observed for some mixtures whose compositions were outside the flammability limits. An SEF propagated a substantial distance from the ignition point, but extinguished before nearing the walls of the pressure vessel. As opposed to a simple, failed ignition, the energy release before extinguishment was orders of magnitude larger than the ignition source energy. SEFs have only been observed in microgravity, and for mixtures whose Lewis number¹ (Le) was less than 1. It is believed they are a result of the interaction of flame front curvature, unequal rates of diffusion of thermal energy and reactants (when $Le = 1$), and radiant heat losses.

Another new phenomenon, called Double Flames, was also recently discovered by Prof. Paul Ronney and his graduate students, when they combusted certain rich H_2 - O_2 - CO_2 mixtures. At CO_2 concentrations below 55.0%, nearly spherical flame fronts were observed; however at 55.0% CO_2 , after a flame front propagated to near, but not to, the chamber wall, a second flame front appeared spontaneously and propagated all the way to the chamber wall. At 55.1% CO_2 , only a single SEF-like flame, similar to the first flame at 55.0% CO_2 , was observed. At 55.2% CO_2 or greater, only non-ignitions were observed. Apparently, despite being overall fuel-rich, there is some residual O_2 not consumed by the first flame which is subsequently reacted in the second flame, i.e. some unconsumed oxygen must leak through the flame front.

DROPLET COMBUSTION: Understanding the basic physical mechanisms acting in the

combustion of droplets, either alone or in arrays, is of longstanding scientific interest and of application to commercial combustion systems. The important scientific issue which can be addressed without the masking influences of buoyancy is the understanding of flame structure, burning rates, limits of flammability, chemical kinetics, as well as transport phenomena, particularly the role of thermophoretic forces. Historically the experimental study of a single droplet under quiescent conditions in normal gravity has been limited to exceedingly small droplets suspended on fibers or falling in co-flowing oxidizer streams. The microgravity environment allows much larger droplets to be studied, hence more accurate visualization and probing of the combustion process can be attained. A microgravity droplet combustion experiment -- currently being performed in the NASA Lewis drop towers and which may require space flight -- attempts to match more closely the assumptions of classical theory than is possible in normal gravity experiments.

The experimental apparatus allows for single droplets to be deployed and ignited with post-deployment residual velocities as low as 2 mm/sec. While the experiment is focused on measuring the time-varying droplet and flame front sizes, sudden fragmentation of n-decane droplets in air has been observed on some occasions. The observed disruption phenomena appears to be connected to collapse of the soot shell surrounding the droplet, on to the droplet itself. Local sites are rapidly heated, and subsequent rapid local vaporization causes the physical disruption of the droplet.

A theory is currently being developed to explain the quasi-steady location of the soot shell. The mechanism of instability of the soot shell is unknown. This interesting effect interferes with the measurement of burning rates and extinction diameters. Near term studies focus on attempting to avoid this effect, so that complete combustion histories can be attained. Additionally, studies of

other fuels including heptane and methanol are underway.

PARTICLE CLOUD COMBUSTION: The study of combustible particle clouds is of fundamental scientific interest as well as a practical concern. Such clouds serve to spread fires in underground mining operations and contribute to the fire and explosion hazards of grain storage and handling facilities. Analogous to premixed gas combustion, of principal scientific interest are the characteristic combustion properties, especially flame structure, propagation rates, stability limits, and the effects of stoichiometry, transport phenomena, and nonadiabatic processes on these properties.

Experimental study of quiescent, uniform particle clouds has not been accomplished in normal gravity due to particle settling and forced or buoyantly-induced air flow. A reduced gravity experiment has been performed recently which emulates the characteristics of classical premixed gas studies and minimizes particle settling and buoyantly-driven flows. In the experiment, a flame propagates through a particle cloud suspended inside a standard diameter flammability tube. A cloud uniformity on the order of 10 percent of the mean concentration was achieved. For fuel-rich mixtures, quasi-steady flame propagation was observed.

The observed shape of the flame front and wake structures were as anticipated but not previously obtained. Of greatest interest is the finding that for near-stoichiometric mixtures, a new mode of flame propagation was observed, now called a "chattering flame." These flames did not propagate steadily through the tube, but instead induced an (Kundt's tube) acoustic disturbance which may have segregated the air-suspended particles into alternating fuel-rich and fuel-lean laminae. Theory has been developed which shows that radiation from combustion products could heat the successive fuel-rich laminae sufficiently to

cause autoignition. The flame then could propagate in a leaping, or chattering, fashion from one fuel-rich regime to the next.

MICROGRAVITY FLUID PHYSICS EXPERIMENTS

A characteristic time for many fluid experiments may be found from L^2/ν , where L is a characteristic length of the system under study (e.g. vessel diameter or height) and ν is the kinematic viscosity. For most reasonably-sized liquid systems, this time is in excess of the time available in ground-based facilities. Thus, to date, most of the microgravity fluid physics research has been conducted in sounding rockets or space. However, the following two studies were recently conducted in our drop towers and aircraft.

LIQUID REORIENTATION: Liquid reorientation studies are particularly important to determine if and how much liquid (e.g. fuel) may be pumped in low gravity to or from a reservoir. There is a large existing literature regarding the equilibrium configuration a free liquid surface will achieve in reduced gravity, this configuration being a surface with constant curvature. The required time to reach this configuration is less studied for the case of sudden changes in gravity level, e.g. from normal to reduced gravity, as occurs in many drop tower experiments. The particular interest of a recent study was to determine the reorientation time as a function of several variables of potential effect, e.g. contact angle, viscosity, fill level.

A simple apparatus was constructed for use in the NASA Lewis 2.2 sec drop tower for measurements to be made to determine the time required for cylindrical, liquid-gas systems to reach an equilibrium configuration when exposed suddenly to a reduction in

gravity level. A barrier coating (3M FC 721) was applied to the container to change the contact angle between the container wall and the liquids, allowing the contact angle effect to be isolated. A variety of constant-contact-angle, silicone oils from the Dow Corning 200 series was used to isolate viscosity effects. High speed photography was utilized to determine the meniscus position over time; in some cases flow visualization was accomplished by use of a He-Ne laser light sheet and plastic tracer particles, with the image recorded by an onboard video system. An empirical correlation for the reorientation time was developed, based on a detailed scale analysis. The correlation has been tested successfully against data from other facilities and other fluid systems.

TWO PHASE FLOW PATTERNS: The objective of these studies by Prof. A. Dukler and coworkers at the University of Houston and by John McQuillen and coworkers at NASA Lewis is to develop and experimentally verify theoretical models that predict two phase flow regimes and characteristics in a reduced gravity environment. The flow regimes have application to the design of heat exchange systems and gas-liquid separation systems in that the flow regime affects pressure drop and heat transfer characteristics.

Experiments have been conducted in the 2.2 sec drop tower and the NASA Lewis Learjet. In addition to "zero gravity trajectories" (actually on the order of ± 0.02 g), the Learjet has flown trajectories to achieve lunar gravitational levels to support NASA's recent Space Exploration Initiative. These experiments have shown that gravity substantially alters the characteristic liquid and gas velocities defining the transitions from one flow pattern to another (e.g. between slug and annular flow; between slug and stratified flow).

INSTRUMENTATION

DROP TOWERS: Influenced predominantly by the harsh operational constraints imposed upon drop towers, diagnostic apparatus historically has been relatively primitive and predominantly qualitative. High speed movie cameras captured flow and flame behavior and recorded LED displays from conventional transducers. High speed data recording was therefore limited by the time required to update the displays and by the camera speed. Recently several new, microprocessor-based, data acquisition and control systems have been incorporated. The most commonly used system in the NASA Lewis 2.2 sec drop tower is founded on a commercially available board, providing 16 digital input/outputs, 10 analog channels, 10 bit A/D conversion, synchronized sampling rates of 100 Hz/channel, and is programmable in a restricted set of BASIC commands.

Flow visualization has been accomplished by use of 1, 5 and 10 mW, He-Ne lasers, commercially available and shock-tested to a level of 30 g's. They are cushioned against impact by the technique described below. Some care must be taken with the alignment of associated lenses because the position of the laser can shift when the experimental package is released from normal to microgravity, since the cushioning material "uncompresses" in the absence of the weight of the laser.

Video imaging has been accomplished with commercially available, miniature cameras which have been shock-tested to 70 g's. Recording is done in two ways: first, an onboard, standard, 8 mm video recorder, surrounded with shock-absorbing foam, has been successfully used. The video image is scrambled briefly (about 0.5 sec) on impact, due most likely to the tape sliding out of its track. In order to both prevent the scrambling and to reduced the physical volume of the onboard instrumentation, fiber

optic transmission of the video camera signal has also been successfully accomplished. Here, the fiber optic cable is routed from the camera, through the drag shield, and back to a video recorder kept at the top of the drop tower. In this way, real time monitoring of the experiment is also possible. In order to minimize the drag induced by the cable, it is already unspooled and hung in a "U-shape" prior to the drop.

Because the deceleration on impact can exceed the levels for which the above instrumentation has been shock-tested, the lasers, cameras, recorders, and delicate electronics have been cushioned in shock-absorbing foam sheets, identical to those used in the rollbars of racecars and in some hospital beds to prevent bedsores. This technique greatly extends the lifetime of the instrumentation.

AIRCRAFT: Because AC power is available and the impact loading is relatively small, aircraft instrumentation can be more standard - closer to that used in normal gravity laboratories - and therefore more sophisticated than those of the drop towers. Standard, rack-mounted data acquisition and control systems and imaging systems are commonly employed. Of special note is the intensified array video camera recently used to photograph low gravity, solids' combustion, when the dim flame's luminosity could not be easily detected using standard cameras.

PLANS FOR INSTRUMENTATION DEVELOPMENT

In response to the growing need for diagnostic amenities, several new efforts are underway for the development of advanced measurement systems which are compatible with the various reduced gravity research facilities. In the absence of the relatively strong force of natural convection, microgravity combustion phenomena are

generally more fragile and easily perturbed than their normal gravity counterparts. Hence, the primary emphasis has been placed on nonintrusive optical diagnostic techniques. Unfortunately, the majority of those techniques currently employed in terrestrial laboratories are intractable in their present forms due, for example, to unrealistic levels of power consumption, or inordinate degrees of system complexity.

The specific measurement parameters most generally of interest have been categorized into the following four areas: i) flow visualization and qualitative imaging, ii) temperature and species concentration fields, iii) velocity fields, and iv) particle size distributions and concentrations.

Two 2.2 sec drop tower experimental packages are being constructed specifically for the purpose of improved diagnostics. The first diagnostic package will be a dedicated platform for a rainbow schlieren imaging system. In addition to its utility for qualitative flow visualization studies, this system has demonstrated the capability for mapping of the quantitative refractive index field with a sensitivity comparable to that of conventional interferometry. The application will be for the measurement of temperature and concentration fields. The second package is being configured to support particle image velocimetry, soot absorption, scattering, and sampling experiments. More distant plans are to incorporate a compact, solid-state laser doppler velocimeter.

Most notable in these packages is the incorporation of a rigid optical platform which is shock-isolated from the drop frame itself by a tunable spring/damper system. In this manner, the relative alignment of the various optical components is insured, while permitting more fragile components or assemblies than currently being utilized. Initial measurements of the degree of shock isolation are encouraging.

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1. The Lewis number is defined as the ratio of the thermal diffusivity of the bulk mixture to the mass diffusivity of the "stoichiometrically deficient" reactant.



Report Documentation Page

1. Report No. NASA TM-103189		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle New Findings and Instrumentation from the NASA Lewis Microgravity Facilities				5. Report Date	
				6. Performing Organization Code	
7. Author(s) Howard D. Ross and Paul S. Greenberg				8. Performing Organization Report No. E-5575	
				10. Work Unit No. 674-22-05	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for the Second Workshop on Microgravity Experimentation sponsored by the National Research Council—Canada, Ottawa, Canada, May 8-9, 1990. Several portions of this document are taken verbatim from NASA TM-101424. Although several changes have been made, the contributions of Don Gotti (instrumentation), John Haggard (droplet combustion), and Prof. Paul Ronney (premixed gas) are acknowledged.					
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17. Key Words (Suggested by Author(s)) Microgravity science			18. Distribution Statement Unclassified—Unlimited Subject Category 29		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 8	22. Price* A02

