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MICROGRAVITY COMBUSTION FUNDAMENTALS

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INTRODUCTION

Systematic investigation of fundamental and applied combustion phenomena has been actively pursued for a number of decades. These efforts have usually been motivated by technological need in such diverse areas as ground and air transportation, electrical power production, and fire prevention. Naturally all such work has been done in the gravitational environment of the Earth, and an accounting of gravitational influence, while sometimes negligible, has usually been required. The growth of manned presence in the low-gravity environment of Earth orbit has provided a new technological need for directed combustion research related to spacecraft fire safety and at the same time has provided the means to pursue fundamental and applied combustion research in a low-gravity environment.

The earliest work in low-gravity combustion in the United States was related to the assessment of fire hazards in spacecraft (ref. 131). The flammability of certain test materials and the effectiveness of several candidate fire-extinguishing agents were evaluated in a quiescent, low-gravity environment. Based on the results of these quiescent chamber tests, material-screening test standards were established for spacecraft material selection (ref. 4). Other early work in low-gravity combustion was of more fundamental character, concerned more generally with using the low-gravity environment to simplify the physics of normal-gravity phenomena. Work of this sort was pursued in the area of premixed gases (refs. 136 to 139), unpremixed gases (refs. 140 to 143), solid-fuel flame spreading (refs. 144 to 146), droplet combustion (ref. 147), dispersed fuels (ref. 148), liquid pool fires (ref. 149), and smoldering (ref. 150).

Advances in the fluid mechanics of combustion have led us firmly to the conclusion that the equations describing energy, momentum, and mass balances, and chemical reaction rates are coupled. Changes in the body force, or gravitational terms in the equations describing fluid motion, result in changes to the coupled terms in the other system equations, which, in turn, again influence the fluid motion. Were the equations uncoupled, body force changes in the momentum balance would affect only the solution for fluid motion, and the other processes would be unaffected. Thus while low-gravity combustion research is a useful tool for understanding normal-gravity applications, care must be taken to avoid overgeneralizing the interpretations of low-gravity experimental results. Careful modeling work is an indispensable corollary effort to combustion experimentation, in order to correctly apply the results from one gravitational environment to another.

The application to spacecraft fire safety of our understanding of the physical and chemical processes that dominate combustion in low gravity is somewhat easier to achieve. Hazard analysis, and fire detection and intervention strategies can be derived more directly from low-gravity results. On the other hand, as a practical matter the screening of materials for use in spacecraft must be performed in ground-based, normal-gravity laboratories. Fundamental low-gravity combustion research is thus essential until a knowledge of

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the fundamental processes involved is adequate to establish a well-understood relationship between low-gravity experiments and ground-based material screening tests.

What follows is a brief summary of some of the important physical processes involved in low-gravity combustion. While discussion is generally limited to the processes involved in the combustion of continuous, solid, nonmetallic fuels, much of the reasoning presented can be applied to other fuel types and configurations. To the extent that the contributing mechanisms are known and understood in various fire scenarios, strategies can be developed to retard or prevent their progress. As low-gravity fire scenarios may require the consideration of some mechanisms normally considered as having secondary importance, some of these mechanisms may in this context be investigated in some detail for the first time. The value of such knowledge is accentuated in spacecraft fire planning because of the high cost of fire safety provisions and the even higher cost of failure.

COMBUSTION MECHANISMS

The ignition and propagation of a fire is an interplay of rate processes including the generation of fuel vapor, one or more fuel-air mixing mechanisms, heat release from the chemical reaction, and the allocation of that heat to fuel generation, mixing, and dissipation.

Fuel Generation

Fuel generation refers to the delivery of fuel to the vicinity of the flame zone, which is most often located in the gas phase. In the burning of solid or liquid fuels, the generation of fuel is generally some combination of chemical decomposition, or pyrolysis, and a phase change, such as evaporation, sublimation, or melting and evaporation. The phase change involves substantial expansion of the fuel and thereby influences the gas-phase flow field. Contributions to the flow field from fuel generation can be quasi-steady or precipitous and chaotic, and they are generally difficult to analyze.

Fuel generation also involves an energy exchange between the phases. Latent heats associated with phase changes and pyrolysis reactions act as net heat sinks with respect to the propagating flame. The feedback mechanisms of heat to the fuel surface generally include conduction, convection, and radiation, and they are complicated by the presence of soot in the gas phase and fuel charring on the surface. For purposes of fire extinguishment, the feedback loop of fuel generation and heat transfer to the surface may be the most important focus of intervention strategies.

Mixing

The fuel-air mixing mechanisms in the propagation of flames are in each case a combination of bulk fluid motion acting in the presence of the diffusion of fuel vapors, oxygen, inert gases, and combustion products. Bulk fluid motion can be induced by several mechanisms, including buoyancy-driven (density gradient) flows, externally imposed, forced (pressure gradient) flows, and the flows associated with the pyrolysis/vaporization of the condensed-phase fuel (mass addition). The spread of the flame into regions containing fresh fuel and air and the flows driven by surface tension gradients of molten fuel can also contribute to the mixing process. In order for a flame to exist and

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propagate, the aggregate mixing mechanisms must be effective to maintain a zone of flammable fuel-air mixture near enough to the existing flame to be continuously ignited.

Concentration-gradient diffusion of species on a molecular level is the most fundamental of the fuel-air mixing processes, wherein fuel vapors from the vicinity of the fuel surface gradually intermingle with the oxygen supply away from the surface. The process is relatively slow compared to the heat release rates required to sustain the fuel generation process. In the absence of additional mixing mechanisms, the presence of inert gases and gas-phase combustion products retard diffusive mixing of fuel and oxygen still further, such that the fuel vapors and oxygen must diffuse through a generally thickening layer of chemically inactive species to sustain adequate mixing rates. Thus systems dependent solely upon diffusion as the mixing process would generally fail to sustain a flame.

In normal-gravity fires large density gradients are created by rapid heat release in the flames. Under the influence of gravity these density gradients cause substantial natural-convection or buoyancy-driven flows, which often entirely overwhelm other fuel-air mixing processes. The coupling of buoyancy to heat release rates, other mixing mechanisms, and chemical reaction rates makes these flows difficult to analyze. As a result, progress in the understanding of normal-gravity fire spreading has been through the implementation of full-scale testing of a variety of configurations. Removal of the gravitational influence in the study of fires that might occur in a spacecraft exchanges this one mixing mechanism, which is difficult to analyze, for other, more subtle mechanisms, only one of which is molecular diffusion. The identification and evaluation of these subtleties have direct application in the analysis of low-gravity fires.

Ground-based, low-gravity experiments have shown how small fluid disturbances affect the perceived flammability of a material. An early approach to quiescent flame-spreading tests in drop towers was to reserve the limited low-gravity time (less than 6 sec) for flame propagation and to ignite the test samples before the drop release. Fluid motion generated by buoyancy during a normal-gravity ignition, although in decay after the drop release, often persists throughout the drop test and cannot be ignored. Samples ignited after the drop release in quiescent flame-spreading tests show reduced flame-spread rates up to moderate levels of oxygen content in the air when compared to the predrop ignition tests. While instructive from a procedural point of view, the comparison of these two methods also indicates the importance of fluid motion, which is less energetic than buoyancy-induced motion, to low-gravity flame spreading.

The influence of forced external flows on flame-spreading rates has been studied extensively in normal gravity. In the most general terms, an externally imposed flow, when acting as a mixing enhancement mechanism or as an aid to heat transfer to the fuel surface, increases flame propagation rates. As the strength of the forced flow increases, however, it can serve as a heat sink mechanism and retard flame spreading. Similarly, the forced-flow influence vanishes as its strength approaches that of the buoyancy-induced flow present in all such tests. Although a discussion of these observations is incomplete without including the convective heat transfer effect of the flow, the fuel-air mixing aspect of very low-speed (sub-buoyant) flows is not addressed at all in these experiments. Ventilation of spacecraft cabins for life-support purposes provides such low-speed flows, and its potential impact on low-gravity flammability is a subject of current research activity.

The momentum associated with the pyrolysis/vaporization of fuel at the surface must be included as a mixing process in the analysis of fuels burning in quiescent low-gravity environments. The strength of this mechanism is a property of the fuel material and is related to the latent heat required to generate the fuel vapor and the behavior of the fuel surface during the fuel generation process. Low-gravity experiments in flame spreading have shown that this fluid motion acting together with diffusion can sustain propagating flames in the absence of other mixing mechanisms. The quiescent experiments conducted to date have shown that, for the simple paper samples examined, stable flames can be sustained only at higher oxygen concentrations than are required to burn the same material in normal gravity. Detailed modeling of the process has required the inclusion of the effects of a surface fuel "jet" in order to predict accurately the flame shapes observed in the experiments.

Other materials, having entirely different processes governing the release of gaseous fuel from the condensed-fuel surface, may exhibit a stronger influence of the fuel jet on the flame. Some burning plastic materials melt, then boil, at the surface. Experiments conducted at low gravity on the burning of nylon Velcro samples have shown precipitous release of fuel vapor from bubbles of molten plastic (ref. 146). This mechanism of fuel release and mixing randomly injects fuel vapors into the flame and renders nylon samples, mounted without a heat sink substrate, flammable in moderate oxygen concentrations at low gravity. The bursting of bubbles in molten fuels has also been shown to eject small particles of burning material from the surface. These particles might also serve as additional ignition sources for remote fuel locations. Other plastic samples such as slabs of polymethylmethacrylate (PMMA) form a char on the molten fuel surface that acts to inhibit the vaporization of fuel. Thus the surface behavior of burning materials may become a material characteristic to be considered in the evaluation of fire hazards in a low-gravity environment.

Quiescent experiments performed at low gravity have also shown that nonflaming combustion or smoldering may occur at the surface of exposed materials in low gravity. Samples that have seemed to extinguish during low-gravity tests have reignited upon the resumption of the gravitational influences at the end of the test. Thus the distinction between the propagation of a flame and extinction may not be as clear in the low-gravity environment as it generally is in normal gravity.

Finally, mixing of fuel vapor generated at the surface with the surrounding air can be accomplished by the propagation of the flame along the fuel surface. For fuels requiring relatively small amounts of energy for fuel generation, the flame can race ahead of the accumulation of combustion products and into a continuing supply of fresh oxygen.

The relative importance of the various mixing mechanisms, including molecular diffusion, the presence of forced flow, fuel injection from the surface, and the spreading of the flame into a fresh air supply, is determined by the properties of the fuel and the environment in which it is burning. These relative influences are not well understood and are worthy of additional study. Since fuel properties can determine the dominant mixing mechanism, the classification of flammable materials by mixing-related properties may become a useful tool in spacecraft fire prevention and control.

Heat Release

The rate of heat release from propagating flames is determined by the chemical energy content of the fuel, the ratio of vaporized fuel to the available oxygen at the flame, and the ratio of the time the reactants are in the vicinity of the flame to the time required for the reactants to react. Since only a narrow range of fuel-air ratios will be flammable, the location where flammable mixtures occur and the residence time of the flammable mixture in the flame zone depend largely upon the fuel-air mixing process. Thus the energy release in a propagating flame in low gravity is controlled largely by the low-gravity fluid mechanics.

Heat Distribution

The location of the flame relative to the fuel and, to a lesser extent, the shape of the flame establish the boundary conditions for the active mechanisms of heat transfer from the flame. In the gas phase, conduction from the flame normal to the fuel surface and parallel to the surface in the direction of flame spread must be considered in the analysis of the fuel-generation feedback system. The temperature gradients that drive conducted heat in the gas phase are, in general, distorted by convection. Conduction of heat in the solid phase can also play a significant role. For fuels appearing in engineering configurations, there often exists a heat conduction path normal to the fuel surface, which provides a dissipation mechanism. Depending upon the fuel thickness, heat conduction through the fuel in the direction of flame spread can also participate in the fuel-generation feedback system.

The participating mechanisms in the flow field determine the importance of convective heat transfer. The role of convection is ambiguous, since it can provide both a mechanism to distribute additional heat to the fuel surface and a mechanism to carry heat away from the system. When viewed as a departure from diffusion-controlled flame spreading, the convecting flow field, added to a flame spreading in low gravity, almost invariably will enhance the flammability of materials. Experimental comparisons of normal and low-gravity heat convection in flame spreading are not yet available. Analysis of convection in the low-speed flows associated with low-gravity flame spreading is thus a prerequisite to an understanding of fire scenarios and the development of prevention and control strategies.

The role of radiative transport in low-gravity flame spreading is also not well understood. The optical depth of small-scale laboratory flames that have been observed in low-gravity experiments is small enough to disregard contributions of radiative transport to the fuel surface. On the other hand, the role of radiation may be prominent in dissipative losses from the fuel surface. The behavior of the fuel material surface in the combustion environment, for example, the appearance of a surface char layer, will determine the influence of this mechanism.

LOW-GRAVITY RESEARCH FACILITIES

Ground-based, low-gravity testing has been indispensible in the study of the behavior of microgravity combustion. In addition to providing data on low-gravity behavior, these facilities have provided valuable insight into the transitory behavior of systems. The response of a dynamic system to step or gradual changes in body forces can be used to explore the time scales of the various participating mechanisms. In addition, revelations such as the demonstration of the influence of low-speed flows on material flammability have been obtained.

Two classes of ground-based, low-gravity research facilities are available: drop towers or tubes, and specially equipped aircraft that fly short-duration, free-fall trajectories. The choice of facility for a particular experiment depends upon the elapsed time and the level of reduced accelerations required for the experiment.

Drop towers and drop tubes are truly ground-based facilities that simply provide an unobstructed vertical space in which an experimental apparatus can free-fall. True free-fall is approached by eliminating aerodynamic drag on the falling experiment either by evacuating the drop pathway or by surrounding the apparatus with a drag shield, which permits the apparatus to free-fall within the more slowly falling shield. Relative accelerations within the falling experiments are typically less that 10^{-6} times normal Earth gravity (one g), while test times of no more than 6 sec are available. Experiment containers are decelerated gradually at the end of the test for reuse. Drop facilities using the drop shield technique can provide up to 10 experiments per day.

Low-gravity aircraft provide significantly longer test times, generally up to about 30 sec. The low gravity is obtained by executing a parabolic trajectory maneuver. The maneuver consists of a dive to gain airspeed, followed by a pullup and a nulling of aerodynamic and propulsion forces to achieve a free-fall over a parabolic hump. Finally, the aircraft is pulled up into level flight. The low-gravity test time is bracketed between periods of about 2 g's associated with the pullups. Experiments attached directly to the airframe experience minimum accelerations that are typically about 10^{-2} g, while selected experiments can be allowed to float within a large aircraft to obtain somewhat reduced minimum accelerations. Depending upon the aircraft and the trajectory sequence, up to 40 low-gravity experiments can be performed during a single flight.