CAPABILITIES AND CONSTRAINTS OF COMBUSTION DIAGNOSTICS IN MICROGRAVITY

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I. Introduction

A significant scientific return from both existing and proposed microgravity combustion science experiments is substantially dependent on the availability of diagnostic systems for the collection of the required scientific data. To date, the available diagnostic instrumentation has consisted primarily of conventional photographic media and intrusive temperature and velocity probes, such as thermocouples and hot wire anemometers. This situation has arisen primarily due to the unique and severe operational constraints inherent in reduced gravity experimentation. Each of the various reduced gravity facilities is accompanied by its own peculiar envelope of capabilities and constraints. Drop towers, for example, pose strict limitations on available working volume and power, as well as autonomy of operation. In contrast, hardware developed for space flight applications can be somewhat less constrained in regards to the aforementioned quantities, but is additionally concerned with numerous issues involving safety and reliability.

The Microgravity Combustion Diagnostics (MCD) group exists to provide diagnostic systems of greater sophistication. The group is located within the Microgravity Combustion Science Branch at NASA-Lewis Research Center, and is funded by NASA Headquarters through the Advanced Technology Development Program. Collocation within this branch helps to assure that the focus of the development efforts are consistent with the scientific objectives of both in-house and sponsored investigators. Although the laboratory staff is frequently involved with the design of diagnostic systems for flight project applications, the MCD program operates on an independent basis, and is not responsible for the design of hardware critical to the development schedule of the space flight projects. The personnel presently supporting this area represent the disciplines of instrumentation and optical systems design, spectroscopy, and computer science.

For a variety of reasons, predominant emphasis has been placed on the development of optical diagnostic techniques. Principal among these is the relative fragility of reduced gravity combustion phenomena as compared to their 1-g counterparts. The action of buoyancy induced convection is vigorous compared to the dominant mechanisms affecting reduced gravity combustion, such as thermal and concentration driven diffusion. The essentially nonperturbative nature of optical measurement techniques is, therefore, well suited to this application. In addition, optical techniques are, in general, amenable to the acquisition of multi-dimensional data fields (i.e. imaging). This is an important consideration in the present state of microgravity combustion science, since a clearer understanding of basic phenomenology, including the verification of fundamental length and time scales and dominating physical mechanisms is still being developed. The ability to simultaneously acquire multi-dimensional data is also an important consideration in the conduct of reduced gravity experimental investigations, since many of the facilities (e.g. drop towers and aircraft) provide periods of only limited duration. Space-borne payloads, in contrast, can provide longer operating times, but are restrictive in terms of repeated access to the investigator, in the amount of power and expendables that may be consumed, and in the total amount of combustion products that can be generated and released into the air.

The process of developing diagnostic systems appropriate for microgravity combustion research does not end in the 1g laboratory. There are a number of reasons why this should be the case, the most significant of which is the differing behavior exhibited by most combustion phenomena under reduced gravity conditions. This is most easily seen in the example of qualitative imaging techniques. In one such example, results indicating an apparent threshold for ignition were later revealed to be an actual threshold in sensitivity of the imaging device under consideration. Differences in mixing and transport phenomena impact overall temperature distributions, population yields of individual species, and resulting temporal and spatial scales. Attempts to duplicate all or part of these observations in the laboratory using such tactics as reduced pressures or varying oxygen concentrations have been marginally successful at best. Thus, the true figure of merit for a given technique requires, in the majority of cases, the transition from the laboratory into one of the various reduced gravity facilities. This transition unfortunately carries with it complications of its own. The MCD group at LeRC, for example, attempts to initially deploy hardware in the drop tower facilities whenever possible. This decision is affected primarily by reasons of timely access, rapid turnaround, and cost. Utilization of this particular facility, however, carries with it many of its own peculiarities that are completely removed from where the instrument may ultimately reside. The available working volume and electrical power, in addition to the severe shock loads that occur at the termination of the drop, are among the most difficult constraints that can be encountered. These constraints would not be as significant an issue in the design of a space borne instrument, but result from the decision to pursue the course of development in this specific facility.

The specific experimental parameters of concern are similar to those of interest in terrestrial combustion science laboratories. It is most often desirable to precede detailed and precise quantitative measurements with qualitative flow visualization methods. This provides the investigator with a global picture of the complete process, and serves to guide or refine the specific requirements for the quantitative measurements that are to follow. For this purpose, the MCD group has utilized conventional photographic media, conventional and intensified solid-state imaging devices, ultraviolet and infrared sensitive solid-state devices, reactive seeding methods, and schlieren imaging. The quantitative determination of temperature, species concentration, and velocity fields comprises a significant portion of the diagnostic development efforts. The characterization of droplets and particles are also represented. As will be discussed, the particular constraints associated with reduced gravity experimentation motivate approaches that are often unique to these applications. Recent advances in solid-state laser and detector technologies, however, are rapidly changing, and are placing us in a position more closely resembling those in progress in industrial and academic research laboratories.

II. Physical Constraints

Each of the venues available to the reduced gravity experiment investigator is accompanied by its own unique collection of physical and operational constraints and available utilities. [1] It should be noted, however, that a concern for diagnostic amenities is most often not a major factor in the determination of the appropriate vehicle for any given experiment. The dominant emphasis is justifiably placed on the accommodation of the combustion phenomenon itself, involving factors such as duration, required g-levels, attendant expertise, storage of consumables, thermal and combustion product generation, and safety. While the specifics concerning the available power, volume, etc. of the various reduced gravity facilities have been discussed in the preceding presentations, a number of additional observations are in order.

While affording the most ready access to reduced gravity experimentation, drop towers are unquestionably the most challenging of the facilities in regards to the constraints that they present. Particularly in the case of the 2.2 second facility, the available working volume and electrical power are severely limited. The 5.18 second facility is somewhat more generous, but still limited in comparison with aircraft facilities. The latter has the added complication of being operated under vacuum conditions. An example of the problems that this can create is seen in the behavior of some photographic films, which become brittle and can shatter upon impact. Pressurized experiment canisters have been constructed, but are an additional inconvenience to operate and maintain. Drop towers do not permit tended operation of the package, and are problematic due to impact loading during deceleration. This brings to bear questions not only of survivability of individual components, but of inordinate optical diagnostic realignment requirements subsequent to each test. The MCD group has successfully demonstrated a system for the reduction of deceleration loads. This system is consistently yielding impact accelerations of only 30 to 40 g's, and appears capable of considerable improvement below this level. The free travel required by this system, however, creates the need for a certain amount of free volume. This represents a substantial tax against an already restrictive condition.

Tethers in the drop tower facilities have been used for purposes of data and power transmission. A multi-mode fiber optic system now used routinely offers video-based image transmission. The 100 micron fiber and its protective sheath have negligible effect on the trajectory of the roughly 500 kilogram package/drag shield assembly. This system facilitates real-time viewing of the experiment package, both prior to and during the drop, and also permits the use of off-line analog and digital storage capabilities. A 110 VAC tether has also been employed for power transmission. The substantially larger cable size has proven to be somewhat unwieldy and is seldom used. A near-

IR diode absorption spectrometer presently being constructed under contract by Southwest Sciences, Inc. will be completely coupled via fiber optic tether, and will have one multi-mode transmission fiber and eight distinct single-mode detection fibers. This tethering not only isolates sources and detectors from impact loads, but permits power supplies, signal conditioning, and data logging electronics to be remotely located, thereby freeing up valuable power and volume on the package itself. The transmission of substantial amounts of laser power, particularly in pulsed laser applications, through the required lengths of fiber is still somewhat impractical. Several schemes have been proposed for relaying higher laser powers to the experiment package by allowing an expanded beam to freely propagate through space. Due to the essentially straight trajectory of the package, some schemes appear tractable, but have as yet not been implemented.

Reduced gravity aircraft are in some ways the most forgiving from the standpoint of diagnostic systems. Available utilities and working volume are considerably more generous in comparison to the drop tower facilities. Although the hardware must be capable of withstanding 9-g loads (as required by flight safety), this is modest relative to the drop towers. The possibility of tended operation is also a distinct advantage. While safety related flight-worthiness reviews are mandated, they do not approach the rigor encountered in space flight reviews. The primary pitfall associated with the reduced gravity aircraft is the relatively poor g-levels that are available. This fact alone presents an untenable situation for many investigators. Nonetheless, aircraft remain excellent platforms for the demonstration and trouble shooting of diagnostic instrumentation. Some tests aimed at attaining lower residual g-levels by free floating experiment packages within the aircraft have been conducted. This scenario results in significantly shorter run times, and power and data lines must be replaced with tethers, similar to those described above.

Although sounding rockets have not yet been used by our group, they are under consideration as a carrier for several experiments. From the standpoint of physical constraints, sounding rockets form an intermediary between drop towers and reduced gravity aircraft. Provisions for power and working volume are comparable to those in the 5.18 sec facility, although the geometry of the payload package is somewhat peculiar (long and narrow). While launch loads are considerably less than the impacts encountered in the towers, experiment hardware is subject to pre-flight vibration testing of 50g each axis, over a 20 to 2000 Hz bandwidth. Bi-directional telemetry is available, permitting a limited degree of opportunity for command and control functions

Actual space flight applications carry with them their own unique issues. As discussed in detail elsewhere, available volume and utilities vary significantly, depending on the specific carrier and location under consideration. Operations are tended, but it must be kept in mind that one is always operating through the "eyes, ears, and hands" of the flight crew. As capable as they are, there is always a reasonable limit to the degree of expertise that can be expected. They will never be as intimate with every facet of a given instrument as are those who developed it. Unquestionably the most significant issue for experimenters that is encountered in inhabited spacecraft activities is that of proof of safety under worst case assumptions. The resulting constraints placed on allowable materials, configurations, and procedures can be extremely restrictive. Creativity and perseverance on the part of the payload developer are ultimately balanced by the forces of time and cost.

III. Techniques Under Development

The MCD group has tried to provide nominal coverage of all of the experimental parameters demanded by the current microgravity investigators. Initial priority has been given to qualitative visualization methods, followed by temperature, species concentration, and velocity measurements. Particle (i.e. soot) and droplet measurements are a more recent addition. Prioritization within each area is influenced to a degree by the schedules of both ground-based and flight projects under development. While our group does not have direct involvement in producing flight-worthy systems, acknowledgement must be given to the issues that will ultimately be involved, such as available power and mechanical stability requirements. The following paragraphs provide brief summaries in each of these areas.

Advanced techniques being employed for qualitative visualization include intensified solid-state imaging arrays (including the use of band-filters), infrared imaging, reactive seeding, and Rainbow Schlieren imaging. Microchannel plate image intensifiers provide a net photon gain on the order of 10^5, and have demonstrated adequate sensitivity for all of the processes that have been encountered to date, which includes dilute premixed gas combustion, low pressure gas jet diffusion flames, low pressure droplet combustion, and solid fuels under quiescent conditions. In the case of dilute premixed hydrogen combustion, [2] prior experiments required the use of halon dopants to render them visible. The addition of extraneous chemicals was a matter for concern, particularly as near-limit phenomena were being investigated. The gain afforded by these devices allows the use of narrow bandwidth spectral filters, either to isolate particular emission bands such as that from CH radicals, or to mask the influence of extraneous emissions, such as soot radiation. Photocathodes sensitive in both the visible spectrum and in the UV are being utilized. These devices have been employed on both of the reduced-gravity aircraft, [2,3] but have not yet been deployed in the drop towers. Data on the performance of the impact isolation system mentioned above is encouraging, and will most likely result in the deployment of intensified arrays in drop tower facilities in the near future. These arrays are also slated for inclusion in several flight projects presently under development.

A platinum silicide array has recently been obtained for imaging applications in the near to mid-IR. Suitable sensitivity has been demonstrated in the laboratory to visualize extremely weak flames, even in the presence of narrow bandwidth IR filters. This opens the possibilities for performing two-dimensional temperature field measurements of known emissivity radiators, such as soot or grids of thin (15 micron) ceramic fibers suspended in the flame. These types of fibers are already being utilized in the LeRC 2.2 sec drop tower for the qualitative assessment of temperature distributions in droplets and gas jet diffusion flames. Radiative thermometry can be accomplished by digitizing the output of the array and fitting the response as measured to the Planck distribution function. Point and line measurements of this type have been widely reported; [4] the extension to two-dimensions appears reasonably straightforward.

A more complex characterization of the IR emission spectrum may enable, in certain cases, the determination of major product species concentrations and temperatures. For simple fuels, resolving the spectrum through an appropriate series of bandpass filters may be sufficient, whereas more complex systems may require a more elaborate approach, such as imaging FTIR. A predictive code [5] is presently being utilized to calculate IR spectra for selected flames. The objective is to invert the procedure: the measured emission spectra serving as the input for the calculation of the emitting species and their temperatures.

Rainbow schlieren [6] imaging is also being utilized as a visualization method. Through the use of a continuous color-based filtering scheme, gradients in the refractive index field appear as variations in color. The eye is quite sensitive to these variations in color, much more so than to the grey scale variations provided by conventional knife-edge methods. In addition, the multi-colored images that result are more readily interpreted than the fringe shifts provided by interferometric methods. Several compact optical systems have been designed and constructed, [7] providing the capability for using this method in the drop towers and aboard the reduced gravity aircraft. A method for quantifying the resulting ray deflections has been developed, providing the ability to determine refractive index distributions with a measurement sensitivity comparable to interferometric methods. [8] The resulting instrument is far simpler and mechanically robust than phase sensitive interferometers, and more readily adapted to large fields-of-view.

The MCD group is also providing capabilities to support the acquisition, manipulation, and display of image based data. [9] A dedicated PC-based workstation is available for image processing and analysis, as well as for hardware and software development. Amenities are available for image transfer and archiving among various formats, including 16 mm motion picture film, still photography, and direct digital imaging. Network access has been established, linking this facility to the diagnostics laboratory, photographic laboratory, computer services laboratory, and a variety of PC and Unix workstations serving individual users. A number of analysis routines have been developed, including automated feature tracking and color characterization.

An effort has been initiated very recently to perform two-dimensional (i.e. planar) laser-based temperature and species concentration measurements. The specific techniques under development include molecular Rayleigh scattering, laser-induced fluorescence, and degenerate four-wave mixing. Techniques of this type were not initially included in the scope of the MCD program due to the impracticality associated with the requisite laser sources. Rapid advances in solid-state laser technology have significantly impacted this situation, bringing about the availability of tuneable, pulsed lasers that can be credibly utilized in the reduced gravity facilities. A development contract is presently being negotiated for a pulsed, line-narrowed Nd:YAG/Ti:Al_2O_3 laser with the capability for frequency doubling, tripling, and mixing to access a number of species of interest. This laser is intended to be compatible with the constraints of the reduced gravity aircraft. Several strategies for beam delivery in the drop towers have been proposed, but are not presently scheduled for implementation.

An alternate technique for species concentration and temperature measurements via absorption spectroscopy is also in progress. This system is being developed by Southwest Sciences, Inc., and utilizes high frequency FM modulation and detection to obtain high sensitivity using inexpensive, near-IR laser diode sources. In the initial configuration, a 1.31 micron diode laser will be utilized to detect absolute concentrations of methane and water vapor, as well as the temperature of the latter. The use of high frequency modulation techniques results in shot-noise limited detection, providing a minimal detectable fractional absorbance of 3 x 10^{-6}. Fiber optic coupling will allow the system to be used in the drop towers; one multi-mode fiber will be employed for transmission, and eight separate single-mode fibers for detection. This multi-channel arrangement will enable the inversion of axisymmetric distributions from line-of-sight data by tomography. Through the substitution of appropriate source and detector combinations numerous other species can be accessed, including CO, CO_2, O_2, OH, NH_3, and NO_2.

Two techniques are being developed for velocity field measurements: particle image velocimetry (PIV) and laser doppler velocimetry (LDV). Both require the addition of seed material to the flow to serve as scattering centers. The specific PIV method being employed has been developed by the Optical Measurement Systems Branch of the Instrumentation and Control Technology Division at LeRC, and employs direct recording from video-based image sensors (as opposed to the utilization of an intermediary photographic recording). [10] This method has been successfully used in several liquid phase studies, including the recent flight of the Surface Tension Driven Convection Experiment aboard STS-50. It has also been demonstrated in high speed gas phase flows. [11] An extremely compact pulsed Nd:YAG laser is presently being constructed to provide the capability for performing these measurements aboard the reduced gravity aircraft. Lower velocity liquid-phase flow measurements can be performed using relatively low-power laser sources, and are scheduled to be performed in the 2.2 sec drop tower within the coming year. A compact laser doppler velocimeter is also under construction, [12] and utilizes a temperature stabilized laser- diode source operating at 780 nanometers and a solid-state avalanche silicon photodiode detector. The complete unit measures 65 mm in diameter and 175 mm in length, and is quite rugged. Laboratory experiments are presently being configured using two similar units obtained on loan from the Department of the Navy. An effort is also in progress in the design of a compact and robust signal processor. [13]

Measurement techniques applicable to the study of particles (i.e. soot) are also under development. Soot size distributions measurements are being performed both in the laboratory and in the 2.2 sec drop tower using a pneumatically actuated thermophoretic sampling probe. [14] Small transmission electron microscopy (TEM) grids are rapidly inserted into the flame to collect soot and then withdrawn. TEM images are then analyzed to provide information regarding the primary particles as well as the aggregated clusters. Size distribution measurements via multi-angle light scattering have been performed in the laboratory, but are not presently scheduled for reduced gravity implementation due to the relatively long integration times that are required. In addition, scattering measurements do not provide information regarding the primary particles directly. The probe measurements are complemented by light attenuation measurements to provide mass fraction and number density. This measurement is being implemented in an imaging configuration, wherein threshold sensitivity is exchanged for overall spatial yield. This is a reasonable tradeoff for the present measurements being performed in the 2.2 sec drop tower, where the limited duration of the experiments do not facilitate point-by-point scanning of the soot field.

The vaporization of isolated fuel droplets is being investigated through the application of exciplex fluorescence. [15] The addition of particular dopants permits the formation of liquid phase complexes which exhibit fluorescence at longer wavelengths relative to the monomer state of the dopant material. In addition to providing the ability to distinguish between liquid and vapor phase concentrations, thermometry can be performed from the ratio of these temperature dependent fluorescent intensities. A complementary study is being conducted under contract by United Technologies Research Center [16] for the measurement of flow fields both internal to the droplet and in the surrounding gas-phase. In addition to exciplex fluorescence, the techniques of planar laser-induced fluorescence, gas-phase flow tagging, and particle image velocimetry will be investigated.

A summary of the overall program in diagnostics development can be found in Table 2 of Reference 17. Shown along with each particular method under development is the present status, as well as the currently envisioned plans for incorporation in the various reduced gravity facilities. It should be emphasized that the list of activities undertaken by the MCD group and its associated contractors has a certain flexibility. The results of ongoing investigations, as well as new areas of interest advocated by the scientific community will continue to expand and refine the complement of diagnostic capabilities that are available.

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