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Requirements for Temperature and Species Concentration Measurements in Microgravity Combustion Experiments

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While microgravity combustion studies have proved to be very informative, ground-based facilities do not always provide a sufficient duration of microgravity for some experiments. Thus, it would be advantageous to perform certain experiments aboard the U. S. Space Station. Furthermore, ground-based experiments in drop towers are often limited by the available diagnostics. In particular, most microgravity combustion experiments could benefit from nonintrusive temperature and species concentration measurements but these diagnostics are impractical in ground-based experiments. In order to limit costs for Space Station experiments which employ these diagnostics, a facility must be developed which can be shared by many investigators performing a variety of combustion and non-combustion experiments.

The requirements for a nonintrusive optical diagnostic facility for Space Station are assessed by examining the needs of current and future combustion experiments to be flown aboard the Space Station. Requirements for test section geometry and size, spatial and temporal resolution, species type and concentration range, and temperature range are reviewed. The feasibility of the development of this system will also be addressed. The suitability of this facility to non-combustion experiments in gases and liquids is also considered.

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Abstract

The requirements for nonintrusive optical diagnostics for Space Station combustion experiments are assessed by examining the needs of experiments which are planned to be flown aboard the Space Station. Requirements for temperature measurements, species concentration measurements, test section geometry and size, and spatial and temporal resolution are reviewed. The feasibility of the development of a diagnostic facility is addressed. The suitability of this facility to non-combustion experiments in gases and liquids is also considered.

1. Introduction

While studies of combustion at microgravity (μg) have proved to be very informative, ground-based facilities do not provide a sufficient duration of μg for some experiments. Thus, it would be advantageous to perform certain experiments aboard the U. S. Space Station where much longer duration experiments may be performed. Furthermore, ground-based μg experiments in drop towers are often handicapped by the primitive diagnostics which must be employed due to impact loads and space constraints. These constraints may be relaxed in Space Station experiments. The principle drawback of Space Station experiments is limited flight opportunities, hence advanced diagnostics are essential in order to gain as much information as possible from each experiment. Thus, μg combustion experiments performed aboard Space Station will enable the use of advanced diagnostics and furthermore will benefit greatly from their use. In order to limit costs for Space Station experiments which employ these diagnostics, it appears practical to develop a facility which can be shared by many investigators performing a variety of combustion and non-combustion experiments. In this paper the requirements for such a facility is discussed and a specific facility plan is proposed.

Practically all μg fluid physics and combustion experiments exhibit fluid flow phenomena which are easily disturbed by external influences. Thus, it is essential that non-intrusive techniques, usually some type of optical method, be employed. Furthermore, most fluids are not blackbodies nor even greybodies;

rather they absorb, emit, and scatter radiation weakly and only in narrow bands. Thus, pyrometric techniques are entirely inappropriate for these experiments (except perhaps to measure solid surface temperatures as discussed in section 6); instead, other techniques such as absorption, scattering or fluorescence must be employed. Absorption measurements cannot provide spatial resolution, hence absorption will not be considered further in this study.

2. Characteristics of microgravity combustion experiments

Perhaps the most important characteristic of all combustion and fluid physics experiments for which μg experiments may be expected to provide new information is a low Froude number ($Fr \equiv U^2/gd$, where U and d are a characteristic velocity and dimension, respectively, and g is the gravitational acceleration) at earth gravity. In other words, a system must be "big" and "slow" in a sense if buoyancy effects are to be important. Another important characteristic of these experiments is that for systems at earth gravity which are of reasonable size, the low Froude number stipulation leads one to conclude that the Mach number must necessarily be quite low. Thus, compressibility effects are insignificant and only hydrostatic forces will result in pressure gradients. In gases hydrostatic forces are of course negligible.

Flames are often divided into two categories: diffusion and premixed. In diffusion flames, two phases or components exist which must be mixed before reaction can occur and reaction is usually restricted to a narrow zone where the fuel and oxidant have mixed to near-stoichiometric proportions. In premixed flames the reactants are intimately mixed on the molecular scale prior to the combustion process.

These two types of flames are affected by gravity in very different ways. In diffusion flames, because of the dominant role of mixing, buoyancy effects are significant whenever the Froude number based on the forced convection velocity (not S_u) is small [1]. In the case of premixed flames, however, buoyancy effects are usually unimportant unless the burning velocity S_u is comparable to the buoyant convection velocity, which is usually near limits of flammability [2], ignition [3], or stability [4]. In diffusion flames the reaction zone structure is unlikely to be affected by buoyant forces because of its thinness [1] (and thus its high Froude number), however, in the premixed case buoyancy may affect the reaction zone structure for sufficiently slow flames as discussed in section 5.

3. Representative experiments

In order to determine the most important requirements for Space Station combustion experiment diagnostics, five representative experiments were selected for study. These experiments were chosen for their practical value and because they are among most likely to be performed aboard the Space Station. The representative experiments, recent references, and the principal investigators (PIs) of these experiments are shown in Table 1. These investigators were surveyed to obtain their opinions as to which measurements are the most important for their experiments and what temporal and spatial resolutions are required. From this information, a consensus of the most important diagnostics for Space Station combustion experiments may be formulated.

Experiment	Principal Investigator
Particle Cloud Combustion [5]	A. L. Berlad, Univ. of Calif., San Diego
Solid Surface Combustion [6]	R. A. Altenkirch, Univ. of Kentucky
Single Liquid Fuel Droplets [7]	F. A. Williams, Princeton Univ.
Gas-Jet Diffusion Flames [8]	R. B. Edelman, Science Applications, Inc., Chattsworth, CA
Premixed Gas Flammability Limits [9]	P. D. Ronney, Princeton Univ.

Table 1. Representative experiments

4. Diagnostic requirements

Based on this survey, the following consensus was reached by most of the PIs. While one would like to know everything about the system, the most important measurements are one-dimensional or preferably two-dimensional time-dependent measurements of temperature and (slightly less important) major species concentrations (e.g. fuel, fuel pyrolysis products, oxygen, nitrogen, water vapor, and carbon dioxide). Many PIs also wanted to measure soot particle size and number density in their experiments. Furthermore, two-phase combustion experiments required measurement of condensed phase surface temperature. Gas velocity and minor species concentrations were considered to be less important in most cases. In addition, each experiment was found to have certain specialized measurement requirements.

5. Premixed gas combustion diagnostics

The requirements for diagnostics in premixed gases seemed to form a "common ground" of measurements that all PIs wanted, both in the type of measurements desired and the relevant scales. Because of this, the characteristics of the premixed gas flammability limit experiments are considered first.

The range of temperatures to be measured in μg combustion experiments is the usual range for combustion processes, typically 300K to 2500K. The number densities of major species vary up to 2.5×10^{19} at atmospheric pressure. Obviously it would be desirable to measure species present in much lower concentrations if possible.

In order to determine the characteristic time and length scales of these experiments, we must first estimate the maximum Froude number for which gravitational effects may be expected. This may be accomplished by equating the buoyant acceleration term in the steady 1-d momentum conservation equation with the convective acceleration term, ignoring viscous effects. This yields

$$UdU/dx = g \qquad (1)$$

substituting S_u, the burning velocity for U, and $\delta = \alpha/Su$ for x, where δ is the flame thickness [1] and α is the thermal diffusivity, we obtain

$$S_u^3/\alpha = g \qquad (2).$$

Then the Froude number in this case is

$$Fr = S_u^2/g\delta = S_u^3/g\alpha = 1$$

as one might have expected. Thus, the Froude number must be of order unity or less for buoyancy effects to be important. A typical values of α for flames at one atmosphere would be 1 cm^2/sec, hence $Su \approx 10$ cm/sec or less for conditions where buoyancy would be expected to have an effect. Then $\delta \approx 0.1$ cm and the characteristic time $\delta/S_u \approx 0.01$ sec.

It should be noted that for <u>any</u> flame of sufficient size (i.e. low Froude number), no matter how fast the flame or thin the reaction zone, buoyancy will be important in characterizing the <u>fluid mechanics</u> of the system (but not the structure of the chemical reaction zone.) Only very slowly burning premixed flames have reaction zones which are affected by buoyancy, as the above analysis shows, but even for a very fast flame, as the flame grows larger, a rising "fireball" appears which will eventually be affected by buoyancy. In this case the system is merely a propagating density discontinuity in a gaseous medium, the characteristics of which are well known.

That buoyancy may effect premixed flames with burning velocities below about 10 cm/sec has been shown experimentally [9]. However, much more interesting interactions are found for burning velocities of about 1 cm/sec [9], for which $\delta \approx 1$ cm and the characteristic time is about 1 sec. In order to resolve these time and length scales, resolutions of one-tenth these scales or less are necessary. Thus, the following requirements for Space Station premixed gas combustion diagnostics may be formulated:

Spatial resolution:	0.1 cm
Temporal resolution:	0.1 sec
Time aperture (to "freeze" the system):	0.001 sec
Test section size for 100 x 100 points:	10 cm x 10 cm

These requirements closely match those recommended by the PIs of the other experiments.

6. Special requirements for other experiments

Each of the other experiments have special requirements in addition to the basic ones outlined in section 5. These special requirements are discussed in the following paragraphs. Clearly, some very unique requirements cannot be met by a single common diagnostic facility, and thus should remain specific to the experiment, but it may be possible to satisfy some of these specialized needs in a common facility.

In the gas jet diffusion flame experiment, velocity measurements are considered to be very important. Because this requirement is unique to this experiment, and because velocity measurements require hardware which is very different from the other measurements which are contemplated, it seems that such hardware should be unique to this experiment and not be included in a common facility. Additionally, turbulence measurements may require very high temporal resolution, placing additional burdens on a common facility. Thus is appears that the special hardware needed by the gas jet diffusion flame experiment cannot be shared by other experiments.

In the liquid fuel droplet experiment, droplet surface temperature measurements are considered to be very important. It may be possible to incorporate this feature into a (primarily) gas diagnostic facility, as discussed in section 7. Furthermore, it is desirable to study very small droplets, as small as 0.01 cm. This mandates very fine spatial resolution, at least for the liquid phase measurements. Also, soot particle size and number density are valuable data. It should also be possible to incorporate these measurements into a common facility, as discussed in section 7.

The solid surface combustion experiment requires measurement of soot properties, as discussed above, and surface temperature. In this experiment it may be possible to measure surface temperature by pyrometric means as described in many other papers at this workshop.

The particle cloud combustion experiment is perhaps the most difficult of all to instrument with non-intrusive optical devices because of the very "dirty", particle-laden environment. This rules out the use of optical scattering methods except possibly for rather elaborate coherent scattering processes such as CARS [10]. Thus, gas phase optical diagnostics may prove impractical in this μg experiment. Additionally, particle surface temperature is desired. For these measurements, pyrometric methods may be sufficient if the flame is optically "thick."

7. Recommended facility

Based on the requirements furnished by the PIs, it appears that one facility could satisfy many of the non-intrusive diagnostic requirements of the candidate experiments. The most promising facility identified would employ light scattering techniques to measure gas temperatures and species concentrations, soot particle size and number density, and exciplex fluorescence [11] to measure liquid temperatures. A block diagram of the proposed facility in a gas-temperature or liquid-temperature measuring configuration is shown in Figure 1.

Obviously such a facility must conform to the size, weight, power consumption, and safety constraints imposed by the Space Station environment. While it is uncertain whether the proposed facility can meet such constraints, the proposed facility appears to be the type of system most likely to meet these constraints and still satisfy the diagnostic requirements of the representative experiments.

In this facility, two-dimensional gas temperature and species concentrations measurements could be made by employing Raman scattering techniques [12]. Raman scattering is a relatively simple technique to implement, is species selective, and is applicable to all molecules. The only major drawback to the method is the very low intensity of the scattered light. In the configuration shown in Figure 1, a Kr-F UV excimer laser is employed because of its high power output, relatively high efficiency, and short wavelength (Raman scattering cross-sections are inversely proportional to the fourth power of the wavelength of the incident light.) While others at NASA have proposed to employ excimer lasers in space experiments [13], for safety reasons it may be more practical to employ other light sources, for example a frequency-quadrupled Neodymium-YAG laser. The laser light is focussed onto a multipass optical cell which spreads the light into a thin uniform sheet. The advantage of the multipass cell method of creating the laser light sheet over conventional cylindrical lenses is greatly increased intensity. This method has been employed previously [14]. Interference filters are used to select the Raman scattered light of the species of interest. The laser pulses are synchronized to a rotating filter wheel so that different species may be imaged on

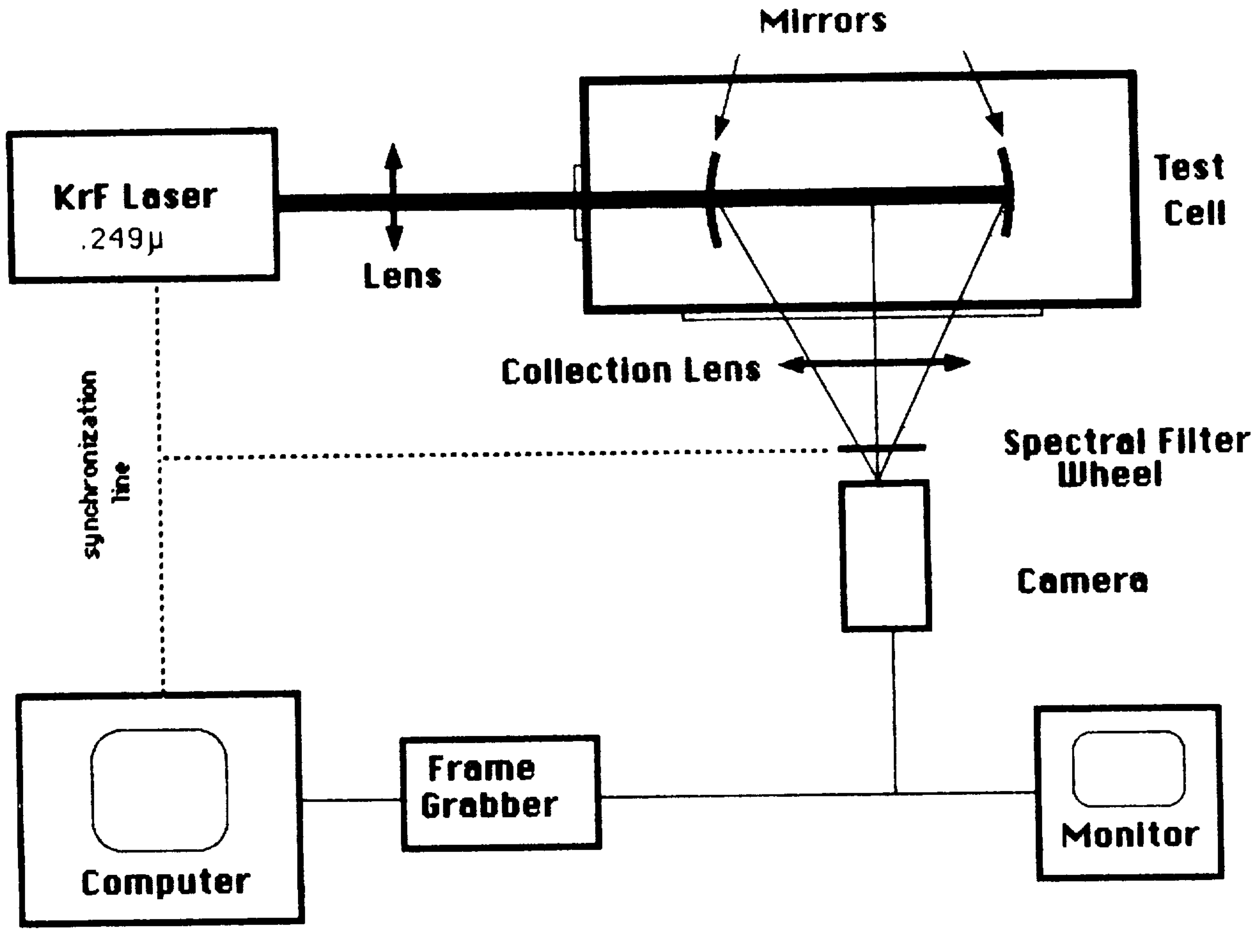

FIGURE 1: Proposed Facility

successive shots. A CID or CCD camera with single-photon sensitivity coupled to a microcomputer data acquisition system is used to image the scattered light. Because of the wide applicability of Raman scattering techniques, this facility may be applicable to many experiments with only a change of spectral filters and imaging software.

The same facility may be used for two-dimensional liquid temperature imaging by means of exciplex visualization [11]. In this method the liquid is seeded with a monomer which may form an excited state dimer, or excimer, with another molecule when the monomer is electronically excited through absorption of photons. The amount of excimer formed varies with temperature. The amount of excimer present may be determined from intensity of its fluorescence signal. Because the same hardware may be used for this technique as for the Raman scattering measurements, it is possible that liquid surface temperature measurements can be made concurrently with gas temperature and gas species concentration measurements on successive laser shots.

The same facility may be used for measurement of soot particle size and number density by Mie scattering techniques [15]. In this case, the multipass optical cell must be replaced by a cylindrical lens and a linear photodiode array for extinction measurements. Measurements could be made only in a one-dimensional system unless it can be assumed that the particle size <u>or</u> number density is constant along the length (parallel to the incident laser beam) of the test section, in which case two-dimensional measurements may be made.

8. Applicability to other experiments

The Raman scattering apparatus can certainly be used to measure gas temperatures and species concentrations in non-combustion experiments where large temperature and/or concentration gradients exist. For small gradients, schlieren or interferometric techniques are probably more appropriate.

This facility may also be used to measure liquid properties in non-combustion experiments. Generally the Raman scattering cross-section of a substance increases slightly upon transition from the gaseous to liquid phase [16]. Because the number densities of liquids are about 10^3 greater than that of gases, Raman scattering of trace species (in addition to major species) becomes practical. However, Raman bands in liquids tend to be broader, hence the Raman frequencies of the components of interest must be well separated. Because of the low thermal expansion coefficient of liquids, it is not practical to measure temperatures in liquids by Raman scattering unless the structure of the Raman spectrum is resolved, a difficult task for single-shot measurements. The exciplex methods discussed in section 7 may be more practical.

9. Conclusions

A wide variety of combustion experiments may benefit from microgravity experiments performed aboard the Space Station. These experiments will require the use of advanced diagnostic techniques. By analyzing several representative experiments, it appears that existing techniques may be able to satisfy many of these requirements. Furthermore, many of the requirements may be met by the use of a single flexible facility with minimal modifications for each experiment. Certain specialized requirements are necessarily experiment-specific.

10. References

1. Glassman, I. Combustion, 2nd. ed., Academic Press, Orlando, 1987.
2. Coward, H.F., Jones, G.W., *U.S. Bur. Mines Bull. 503*, 1952.
3. Lewis, B., von Elbe, G., Combustion, Flames, and Explosions of Gases, 2nd ed., Academic Press, New York, 1961.
4. Clavin, P., *Prog. Energy Comb. Sci.* 11:1 (1985).
5. Joshi, N., Berlad, A.L., *Comb. Sci. Tech.* 47:68 (1986).
6. Vedha-Nayagam, M., Altenkirch, R.A., *Acta Astronautica* 12:565 (1985).
7. Williams, F.A., *Acta Astronautica* 12:547 (1985).
8. Edelman, R. A., Fortune, O. F., Weilerstein, G., Cochran, T. H., Haggard, J.B., *Fourteenth Symposium (International) on Combustion*, Combustion Institute, Pittsburgh, 1973, p. 399.
9. Ronney, P. D., Wachman, H. Y., *Combust. Flame* 62, 107 (1985).
10. Eckbreth, A.C., Bonczyk, P. A., Verdieck, J.F., *Prog. Energy Combust. Sci.* 5:253 (1979).
11. Murray, A.M., Melton, L.A., *Appl. Opt.* 24:2783 (1984).
12. Long, D.A., Raman Spectroscopy, McGraw-Hill, New York, 1977.
13. MacKenzie, B., personal communication, NASA Ames Research Center, 1986.
14. Long, M.B., Fourguette, D.C., Escoda, M.C., *Optics Letters* 8:244 (1983).
15. Vandsburger, U., Kennedy, I.M., Glassman, I., *Twentieth Symposium (International) on Combustion*, Combustion Institute, Pittsburgh, 1984, p. 1105.
16. Weber, A., ed. Raman Spectroscopy of Gases and Liquids, Springer-Verlag, Berlin, 1979.