LASER DIAGNOSTICS FOR MICROGRAVITY DROPLET STUDIES

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ABSTRACT

Rapid advances have recently been made in numerical simulation of droplet combustion under microgravity conditions, while experimental capabilities remain relatively primitive. Calculations can now provide detailed information on mass and energy transport, complex gas-phase chemistry, multi-component molecular diffusion, surface evaporation and heterogeneous reaction, which provides a clearer picture of both quasi-steady as well as dynamic behavior of droplet combustion.[1] Experiments concerning these phenomena typically result in pictures of the burning droplets, and the data therefrom describe droplet surface regression along with flame and soot shell position. With much more precise, detailed, experimental diagnostics, significant gains could be made on the dynamics and flame structural changes which occur during droplet combustion. Since microgravity experiments become increasingly more expensive as they progress from drop towers and flights to spaceborne experiments, there is a great need to maximize the information content from these experiments. Sophisticated measurements using laser diagnostics on individual droplets and combustion phenomena are now possible. These include measuring flow patterns and temperature fields within droplets,[2] vaporization rates and vaporization enhancement,[3] radical species profiling in flames[4] and gas-phase flow-tagging velocimetry.[5] Although these measurements are sophisticated, they have undergone maturation to the degree where with some development, they are applicable to studies of microgravity droplet combustion. This program begining in September of 1992, will include a series of measurements in the NASA Learjet, KC-135 and Drop Tower facilities for investigating the range of applicability of these diagnostics while generating and providing fundamental data to ongoing NASA research programs in this area. This program is being conducted in collaboration with other microgravity investigators and is aimed toward supplementing their experimental efforts.

INTRODUCTION

Measurement Needs

Droplet Internal Flow

While modeling efforts of droplet combustion under microgravity conditions have been expanded to include transport and chemistry,[1] experiments are providing data on droplet surface regression rates along with flame and soot shell position. Even these limited data disagree with theory,[6] possibly as the result of gas-phase convection around the droplet and liquid-phase convection within it. The internal flows may largely be residual from the droplet deployment process in which a droplet is suspended on a hypodermic needle which is rapidly retracted. To understand the results of the experiment, it is necessary to characterize these droplet flow patterns and determine if they can be dissipated over some time delay period.

Gas-Phase Flow

Gas-phase motion over the surface of a droplet can have a profound impact on the droplet burning rate. Droplet deployment can leave droplets with a residual drift on the order of 1-2 mm/sec and as high as 10 mm/sec. Relative gas-phase motion of just a few mm/sec can result in a significant change in the droplet burning rate.[6] The effect of spark ignition can be a dramatic effect; it introduces a perturbation in the gas-phase flow resulting in a second source of residual gas/droplet motion. Techniques for anchoring a droplet in place using either fiber suspension or electrodynamic levitation certainly warrant investigation. These techniques alone, however, may not be adequate without assessing the gas-phase flow, possibly using a flow tagging or velocimetry imaging approach.

Flame Front Position

Knowing the position of the reaction front is important for anchoring computer models. Currently, an approximation of this position is obtained from back illumination images and natural light imaging on a second camera; these characteristics are not likely to be able to be related directly to predicted model parameters in a quantitative fashion. These can be difficult to interpret, since they are a line of sight measurement on a spherical body. Planar laser-induced fluorescence of OH could at least provide representative flame front positions[4]-even if only performed qualitatively. On the lean side of the flame, OH would prove reasonable as a flame front marker. Performed in a time resolved manner, these measurements could provide information on combustion unsteadiness regarding not only flame position relative to the droplet but also the structure of the flame.

Liquid-Phase Thermometry

Droplet combustion can be characterized as a generic gas phase diffusion flame with curvature but no flame stretch. The flame structure is, however, to some degree rate limited by evaporation; the transfer of heat into the droplet is therefore an important influence on the burning rate. Measuring the liquid phase temperature distribution could further the understanding of the flame behavior, particularly for multi-component droplet combustion.

Diagnostic Capabilities

Optical flow diagnostics offer several advantages over physical probes because they permit multi-point measurements non-intrusively. Non-intrusive measurements are of particular importance for droplet combustion and transport in microgravity environments where physical contact would introduce perturbations. The resolution of these diagnostics can also isolate transport to length-scales much smaller than the droplet diameter. These techniques can be configured to instantaneously map an entire flow field in two and three dimensions, providing either qualitative or quantitative information on the distribution of a desired scalar.

Internal Circulation and Quenched Fluorescence

The capability for measuring flow patterns within individual droplets[7] using oxygen quenching of laser-induced fluorescence has been demonstrated. Decane doped with naphthalene was used for the initial experiments. Droplets from a droplet-on-demand generator fall a short distance into a chamber filled with nitrogen and a variable amount of oxygen. A thin sheet of ultra-violet light from the fourth harmonic of a Nd:YAG laser at 266 nm illuminates single droplets. A magnified image of the naphthalene fluorescence is recorded digitally using a two-dimensional vidicon detector interfaced to a laboratory computer. Since oxygen is a strong fluorescence quencher, any liquid volume element which has been exposed to it by surface contact or diffusion will suffer a reduction in fluorescence intensity. Convection from the surface due to internal circulation and diffusion cause oxygenated image regions to appear darker. Oxygen-free experiments provide a baseline case for comparison. These data are shown in Fig. 1. This diagnostic can be used to describe flow patterns within droplets, and for determination of relaxation times for the motion to dissipate.

Exciplex Thermometry

Temperature measurements have been performed within droplets as a function of ambient temperature using two color detection.[2] The temperature measurement technique used is exciplex fluorescence thermometry, which exploits the fluorescence at two different wavelengths resulting from the reaction of an excited dopant molecule to form an excited-state complex or exciplex.[8] The technique was used to measure the temperature along a meridian plane of the droplets. An exciplex system is formed using naphthalene/TMPD in decane. At higher temperatures, the system monotonically shifts to increase monomer selective concentration and monomer fluorescence (blue/violet) dominates, hence, the ratio of monomer fluorescence over exciplex fluorescence (green) and the intensity ratio can yield the temperature. The resulting fluorescence from the droplet is imaged in two dimensions at both wavelength regions. The pixel-to-pixel ratio of these two images can be used, after calibration, to obtain the temperature. This measurement would be especially important for combusting multi-component droplets but due to the sensitivity to oxygen quenching has been used to date in non combusting systems. As will be described below, microgravity droplet combustion may present an ideal opportunity for implementation of this approach since the symmetric envelope flame may preclude oxygen from contacting the droplet fluid.

Levitation and Suspension of Droplets

The aforementioned diagnostic techniques rely on a droplet occupying a known position to allow the laser beam to "slice" through a central plane precisely . The droplet surface acts like a lens, bending the incident rays toward the center of the droplet. The light will appear to not fill the circumference (top and bottom) of the droplet if the illumination sheet is not incident on a great circle, slicing exactly through the center of the droplet. In typical microgravity experiments, slight drifts in droplet position are unavoidable. These drifts may be due to either droplet relative motion within the test chamber, or, g-jitter which is typical of microgravity environments on aircraft. These drifts, however, can be compensated for by either an electrodynamic levitator or an extremely small fiber to tether the droplet.

Producing and supporting a droplet on a thin fiber or filament can be achieved repeatedly with automated deployment. A droplet-on-demand generator can produce a single droplet which is brought into contact with the fiber filament. When the filament has a slight material bead or buildup at some position along its length, the droplet becomes anchored and supported at that position. This arrangement is shown in Fig. 2. The diameter of the fiber and roundness of the bead require careful attention relative to the droplet diameter so as not to change the surface contour of the droplet at the wetting surface of the fiber. With careful consideration, these criteria are easily met. Droplets supported in this manner can be used for experimentation even in the presence of g-jitter. It should be noted that while the g-jitter effects the data quality, it will not effect the success of the experiments.

Flame Front and Gas-Phase Velocimetry

An additional research requirement would be detailing the gas-phase flow field and position of the flame front. This can be achieved using Planar Laser-Induced Fluorescence (PLIF) of OH[4] which is typically performed by tuning a laser to the OH molecular absorption and recording the emitted radiation with a two-dimensional detector. Laser sources and detection systems capable of operating under the power and shock environments typical of drop tower conditions may be available, however, some development is likely to be required. An alternative approach would be to provide laser-induced fluorescence from a diagnostic seed included in the liquid-phase fuel which would be consumed at the flame front. This, in principle, would be easier, and lower risk since the diagnostic capabilities and instrumentation already exist. The main advantage to this approach would be that the wavelength of the molecular absorption involved can be chosen to coincide with convenient laser wavelengths than lasers can be configured to access OH. The details of this approach will be given under the project description.

Gas-phase flow tagging is capable of defining the flow field around the droplet and can be performed in a number of different ways. For post-combustion gas conditions, photodissociating water vapor in known spatial locations and subsequently recording the PLIF of OH yields gas phase velocities.[5] This approach is probably beyond the scope of microgravity applications due to its complexity and instrumentation requirements. An alternative approach would be to use laser-induced phosphorescence, by writing lines in a pre-seeded flow and subsequent imaging the convection of triplet-state excited molecules. In this way, gas-phase velocities and flame positions could be measured.

Particle Image Velocimetry (PIV) holds the potential for recording two-components of velocity in a two-dimensional plane. Conventional techniques like Laser Doppler Velocimetry would not be appropriate because it is a point technique and would not provide information related to the global flow field. PIV uses lasers to illuminate a seeded fluid with two short, properly-timed pulses. In this way, each particle in a sheet of laser light can be illuminated and imaged twice in a frame of an imaging device such as a CCD camera. With this information, spatially resolved maps of two components of velocity can be determined. The proper selection of image magnification, pulse timing, particle size and seed rate, allow a two-dimensional velocity field to be acquired instantaneously. Video acquisition systems and computer software are used to process the images and manipulate them to produce the vector field.

PROJECT DESCRIPTION

Program Plan

The objective of this program is to perform a series of measurements to investigate the range of applicability of advanced laser diagnostics to microgravity applications while generating as much fundamental data to ongoing NASA microgravity research programs as possible. Through consultation with NASA personnel, and other researchers in the field of microgravity droplet transport and combustion, priorities will be established with respect to measurement parameters. The measurement parameters currently under consideration are:

(1) droplet internal flow
(2) relative gas-phase flow around droplets
(3) flame front position
(4) liquid-phase thermometery.

An integrated diagnostic unit, capable of performing these measurements will be assembled. All of the major components such as lasers, detectors and data systems are currently available and allocated to this effort. A self-contained miniature nitrogen-pumped dye laser system and two-dimensional intensified diode-array imaging system will form the core of the unit.

The testing program will proceed with ever more challenging environments proceeding from the laboratory, to flight based tests, and finally, to drop tower facilities. The diagnostic approaches and instrumentation would be verified in a laboratory setting. Experiments with the intent of reducing the risks associated with high impact and droplet drift would be conducted on either the Learjet or KC-135 Aircraft with fiber suspended droplets. Measurements will be performed on droplet internal flow patterns and the applicability of liquid phase thermometry in a burning droplet. Investigations will be made into performing PLIF measurements of OH or a diagnostic seed material to describe flame front position. Gas-phase flow dynamics will be determined by velocity measurements using particle image velocimetry.

Risk Reduction - Flight Experiments

Initial experiments are designed to reduce the risks associated with high impact and droplet drift. Experiments of droplet combustion under microgravity conditions are best if carried out in either the NASA LeRC 2.2-Second Drop Tower, or the 5.18-Second Zero-Gravity Facility, to provide a "clean" set of experimental conditions. Two aspects of these facilities and the environment they provide present the greatest challenges to laser diagnostic implementation. First, the impact at the bottom of the tower can range from 60 -70 g's. Designing advanced instrumentation to sustain these impacts is quite difficult. A risk reduction step is to perform a test sequence aboard the NASA Aircraft Microgravity Facilities. Although the aircraft do not provide as "clean" a microgravity environment, ($\sim 10^{-2}$ g), the diagnostic could be developed while still providing quality data. These experiments would be followed by measurements in the LeRC 2.2-Second Drop Tower.

Isolate Droplet Motion

The second challenge to diagnostic implementation is the droplet drift present in all previous microgravity droplet experiments. As described above, droplet deployment is always accompanied by some initial velocity which is imparted on the droplet. The relative motion of the droplet to the ambient gas can result in significant change in the burning behavior. Furthermore, this motion complicates the diagnostics. To alleviate these problems the experiments can be performed on droplets supported on a thin fiber, or supported in an electrodynamic trap. Fiber support is relatively simple, however, detailed measurements of the effect of the fiber boundary on droplet internal flow patterns would still need to be understood. The operation of electrodynamic traps becomes considerably simplified at low gravity due to the reduced forces on the droplet.

An automated deployment system will be coupled to thin filament suspension. A droplet-on-demand generator will produce a single droplet which is brought into contact with the fiber filament. The filament will have a slight material bead or buildup at some position along its length so that the droplet becomes anchored and supported at that position as is shown in Fig. 2. The diameter of the fiber and roundness of the bead will receive careful attention relative to the droplet diameter so as not to change the surface contour of the droplet at the wetting surface of the fiber. Droplets supported in this manner will be used for experimentation even in the presence of g-jitter. It should be noted that even though the g-jitter effects the quality of the data relative to combustion due to the gas-phase fluctuations, it will not effect the success of the experiments.

Internal Flow Patterns

Initial measurements are directed toward describing the internal flow patterns of droplets in a non-combusting environment. The convection of oxygen dissolved into the surface fluid of an isothermal, non-burning droplet will be detected by the quenching of laser-induced fluorescence. The fluorescence images will be recorded in two dimensions from a laser sheet, provided by a compact nitrogen laser, which slices through the interior of the droplet. This measurement can be performed in a time-phased manner with the introduction of a time delay to evaluate temporal evolution. These experiments could potentially answer questions relating deviations between current experiments and theory.

Liquid-Phase Thermometry

An extension of the flow measurement techniques will provide liquid-phase thermometry using the same apparatus. Laser-induced exciplex thermometry can be employed in a burning droplet, if it could be shown that no oxygen permeated into the measurement regions. This would be expected in microgravity conditions where a symmetric envelope flame surrounds the droplet and consumes oxygen prior to dissolution in the liquid-phase. This assumption is easily verified by repeating the flow pattern measurements on burning droplets. Liquid-phase thermometry would qualitatively confirm modeling assumptions while providing quantitative temperature data.

Flame Front Measurements

Development of the UTRC diagnostic system will be directed toward PLIF of OH. Potentially minor modifications to the nitrogen laser system may allow it to operate on excimer gases such as XeCl, thus providing a means of directly exciting the OH molecule. Alteratively, arc lamp illumination could be used. This would provide image data on the position of the flame front around a burning droplet. A second alternative approach would be to perform laser-induced fluorescence from a diagnostic seed included in the liquid-phase fuel which would be consumed at the flame front. This, in principle, would be easier and the diagnostic capabilities and instrumentation already exist. The main advantage to this approach would be that the molecular absorption wavelength can be chosen to coincide with more-easily-accessed laser wavelengths than those of OH. Several diagnostic materials are available with readily available absorptions, high fluorescence yields, and flammability limits similar to typical fuels, i.e., biacetyl in methanol. For these studies, the nitrogen laser will be used in conjunction with the dye laser tuned to the appropriate wavelength.

Gas-Phase Flow

Particle Image Velocimetry (PIV) holds the potential for recording two-components of velocity in a two-dimensional plane. PIV will be performed using two pulses from the nitrogen laser to illuminate the gas surrounding the droplet after it is seeded with aerosol particles. In this way, each particle in a sheet of laser light can be illuminated and imaged twice in a frame of the imaging system. With this information, two components of the velocity vector will be determined. The proper combination of image magnification, pulse timing, particle size and seed rate, provide instantaneous two-dimensional velocity fields. Computer software to process these images and manipulate them to produce the vector field is currently in use at UTRC.

Conclusions

This research program provides measurements investigating the range of applicability of these advanced diagnostics while generating fundamental information relevant to ongoing NASA programs in microgravity droplet combustion. Using a progressive approach, advanced laser diagnostics will be transported from laboratory, to flight experiments, and ultimately to drop tower facilities. In this way, these diagnostics can be developed, while providing fundamental data on droplet transport and combustion at an early date. The experiments and measurement parameters suggested here, reflect the needs of other researchers in this area. Dissemination of the results of this program throughout the community will effect their research directly. At the conclusion of this program, the technology demonstrated herein will be applicable to future ground based research, as well as space based operation aboard future Shuttle, Space Lab or Space Station Freedom laboratory modules. The facility and techniques demonstrated would serve as a stepping stone for future programs. Development and demonstration of this technology at this time, is a prerequisite for these far reaching goals.

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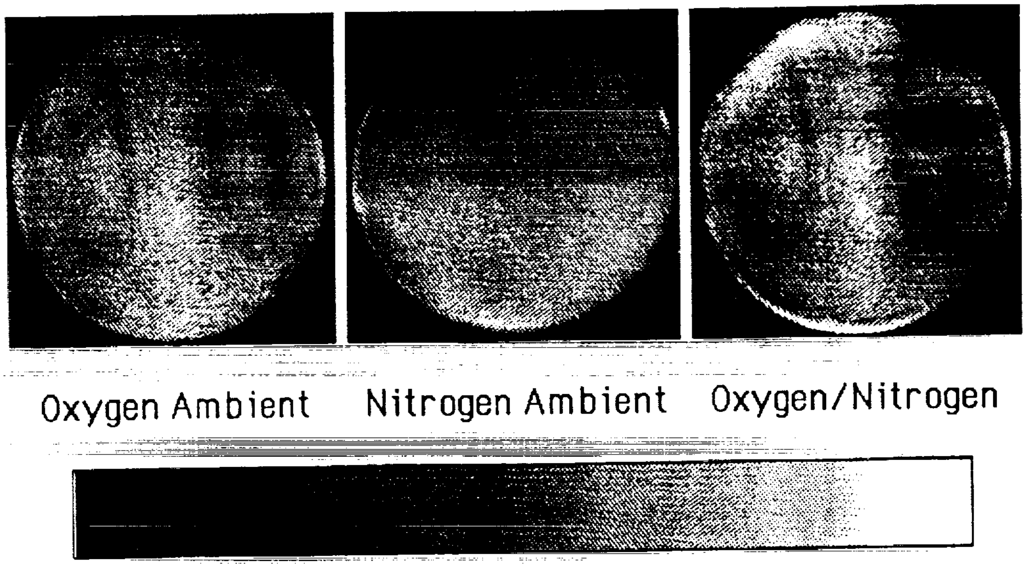

Fig. 1 Measurement of internal circulation from within droplets using fluorescence quenching.

See Color Plate C-7a

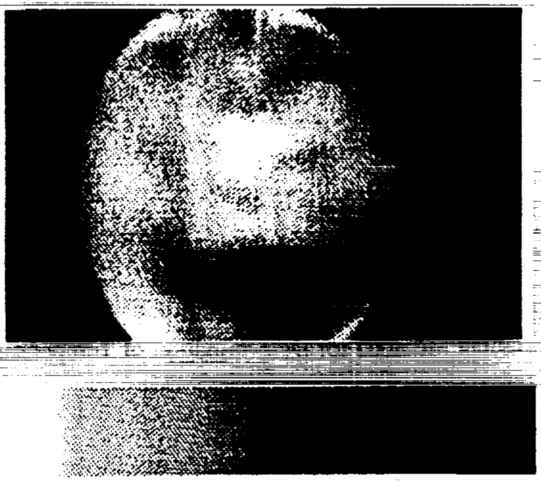

Fig. 2 Surface fluorescence quenching from a droplet supported on a fiber.

See Color Plate C-7b

COMMENTS

Question (A. Gomez, Yale University): In an electrodynamic balance, typically, a DC field is used to counterbalance gravity and AC field is used to provide lateral stability. In the microgravity experiments the g-field is highly variable. Have you thought about a feasible feedback system to accurately change your DC voltage over several orders of magnitude?

Answer: The electrodynamic balance can be operated with a DC field, an AC field, or a superposition of both. In one-g, the gravitational influence is typically offset with the DC field, and the AC field is applied to provide lateral stability. The levitator can, however, be operated stably with just the AC field even at one-g, eliminating the need to actively adjust the DC voltage for changes in gravitational field or droplet mass. Since the AC field provides a force towards equilibrium corresponding to an opposite velocity of the droplet, strong AC fields tend to overdrive the droplets resulting in oscillations. The AC frequency must be tuned for stability, corresponding to a reaction time-constant relating droplet inertia and drag. Our experience has shown that for droplets in the 500 micron diameter range at atmospheric conditions frequencies of the order of 400 Hz are most appropriate.

Question (C.T. Avedisian, Cornell University): How do you plan to "calibrate" your approach for flame diameter measurement based on CH identification? For example, do you plan to compare flame diameter measured from photographs with your laser based flame diameter?

Answer: In hydrocarbon flames, CH radical laser-induced fluorescence is accepted in the literature as the best indicator of most intense chemical reactions. While photographic recording of broadband flame luminosity is often used for indicating flame positions, these measurements suffer from both spatial ambiguity associated with line-of-sight observation, and assumptions related to non-equilibrium chemistry and excited-state radical-species formation. Comparisons will be attempted between luminosity observations and the laser-induced fluorescence flame front indicator to be used in this study, to establish correspondence between the approaches.

SESSION D - PREMIXED FLAMES

(Chair, Mitchell Smooke)