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Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

New Particle-Image-Velocimetry Method to Measure Flowfields in Luminous Spray Flames

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Introduction

SEVERAL investigators have used particle-image-velocimetry (PIV) diagnostics to determine the flow characteristics of a range of laboratory-scale and practical devices that vary in geometry and flow complexity under isothermal flow (normal temperature) conditions.[1–3] In PIV the flow is seeded with submicron-sized particles, and the motion of these particles is used to determine the gas-phase velocity. The size and density of the particles depend on the nature of the flow characteristics. The flow velocity is determined from double exposures of these particles taken at a very small and known time interval. The flow velocity is determined by measuring the distance a given particle travels between the two consecutive exposures of the same particle. The particle size is very small and can flow the flow at high frequencies so that the flow velocity is the same as the particle velocity. In the case of luminous flames, the determination of flow characteristics has not been possible before because of the high background signals emanating from flames during the combustion of fuels.

Since the introduction of PIV as a diagnostic technique, considerable progress has been made to develop systems that can extract information on the flowfield from any number of angles and in three dimensions.[1–3] The diagnostic technique provides instantaneous information on the entire flowfield for mean and rms values of axial, radial, and tangential components of velocity, vorticity, strain rates, and other flow characteristics. Such detailed characterization of a flowfield would take significantly longer time using other nonintrusive diagnostic techniques, such as laser velocimetry, photon correlation, or double-spark photographic techniques. For the first time it is now possible to visualize the entire flowfield in three dimensions so that one can make direct comparisons of the flow features with calculations. Systems with as many as six cameras have been utilized in the literature to analyze a wide variety of flows under normal temperature conditions of flow, ranging from simple laminar to more complex turbulent and supersonic.

In principle, PIV diagnostics can be used to provide important information on the flow and turbulence characteristics of any kind of flow under both isothermal and combustion conditions. However, PIV observations within luminous or semiluminous flames have been problematic. The radiation from the flame tends to overwhelm the illumination of the laser sheet beam, thus preventing the acquisition of useful information about the movement of droplets, particles, or seeded particles in the flow. In the case of spray flames, the flames in the near vicinity of the burner exit are often luminous, so that illumination of the flow with a laser beam results in only overexposed background signal levels, that is, no information is obtained on the transport of droplets or small submicron-size particles seeded in the flow from which information on droplet velocity or particle velocity (and hence the fluid flow) is determined.

This technical Note documents the development of a new PIV system that incorporates narrow-bandpass filters and mechanical shutters, which can be used to alleviate the problem of high background flame radiation. The new method has been successfully used to observe the behavior of fuel droplets and/or very small size seed particles within the highly luminous kerosene spray flames from which information on the mean and turbulence characteristics of the flow associated with the droplets and carrier phase is determined.

Facility Design

A swirl-stabilized kerosene spray flame was used to obtain a luminous flame for flow diagnostics. The PIV system discussed next was used to observe the dynamics of fuel droplets and seed particles introduced into the combustion airflow to determine the airflow motion. The burner used was a double concentric swirl burner having fuel spray located at the center of the burner. Air was supplied to the burner through two concentric air annuli. The swirl angle and airflow rate distribution in the two annuli could be varied independently.[4] A commercially available air-assist spray nozzle was used to create a hollow cone fuel spray, with a mean droplet size of approximately 50 μm. The airflow and swirl angle could be used to alter the spray structure considerably.[5,6]

The specific flames examined here are highly luminous and represent characteristics similar to those observed during the combustion of solid fuels, propellants and high energy density fuels that have the propensity to produce high levels of soot. The high background luminosity from flames masks the scattered light signal produced from the submicron-size particles, droplets, or particles. A sample photograph of the luminous kerosene spray flame used for flowfield diagnostics, showing high background flame luminosity, is shown in Fig. 1. To take meaningful data from within such a flame, the PIV system had to be able to deal with the broad-spectrum radiation produced from the flames.

PIV System

The specific system used here was a three-dimensional PIV manufactured by Integrated Design Tools (IDT™). A schematic diagram of the system is shown in Fig. 2 and consisted of the following: 1) a solo PIV Nd:YAG pulse laser containing two laser cavities which fire independently; 2) two 1280 X 1024 pixel charge-coupled device (CCD) cameras (sharpVISION™ 1300-DE, model Sony ICX085AL CCD) equipped with 532-nm narrow-bandpass filters having a bandwidth of 0.87 nm); 3) mechanical shutters that

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Fig. 1 Photograph of a luminous kerosene spray flame.

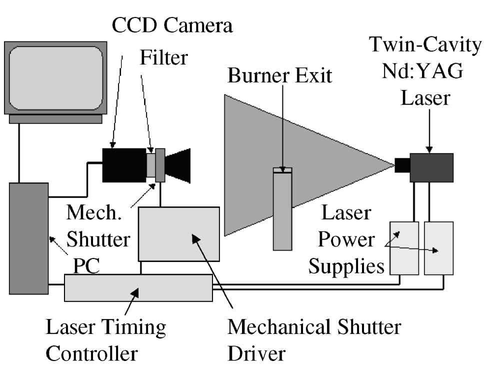


Fig. 2 Schematic diagram of the PIV facility.

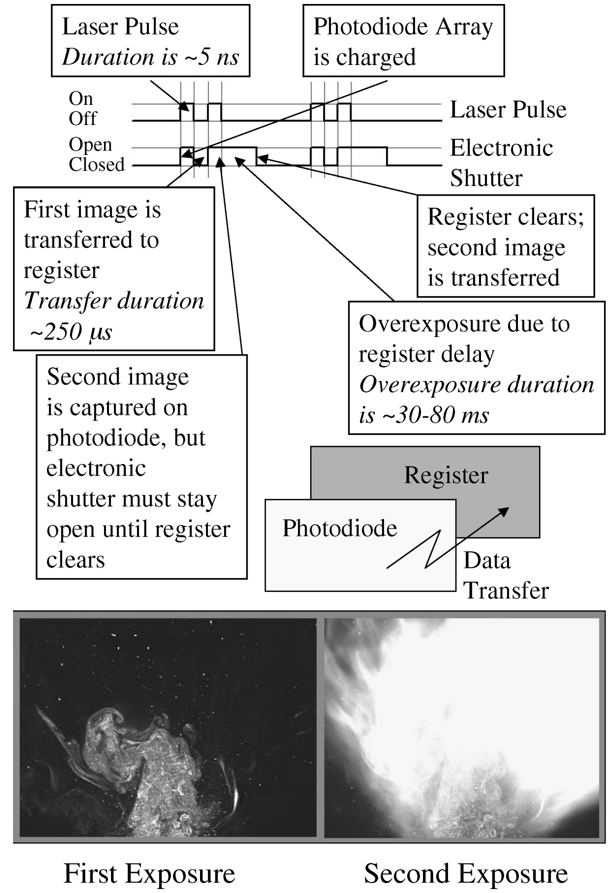


Fig. 3 Operational cycle of conventional PIV system without mechanical shutter.

regulate the light entering each camera; 4) power supplies for lasers and shutters; 5) IDT 1000 PIV system, which acts as a controller to synchronize the laser pulses and cameras; 6) IDT 2000 control modules for the cameras; and 7) a PC equipped with the boards and the appropriate software necessary to acquire the images from the cameras and their subsequent analysis to obtain information on the velocity and turbulence characteristics. (Velocity vector data generated by the software were then plotted and displayed using Tecplot™ software.)

The laser is used to project a thin sheet of coherent light through the region of interest. The pulse duration of each laser cavity is on the order of nanoseconds. The delay time between pulses can be adjusted in order to respond to different flow conditions.

The PIV measurements depend on capturing pairs of images separated in time of the order of nanoseconds. The fundamental problem to be resolved when attempting to carry out PIV diagnostics in high luminosity flames is to prevent overexposure of the photodiodes in the cameras during the two exposures. CCD chips used in PIV employ electronic shutters, which, when open, make the photodiode sensitive to incoming radiation. This electronic shutter opens before the first laser pulse is fired (see Fig. 3). When the first laser pulse is fired, the light captured by the optics falls on to the photodiode array of the CCD camera. The impact of the photons on this array causes electrons to migrate into potential wells corresponding to each pixel. The electronic shutter then closes, and the charges developed on the photodiode array are transferred to the horizontal register, a process that, for CCD cameras, takes approximately 200 to 250 μs. The electronic shutter then opens again, and the second image illuminated by the laser sheet beam is then captured, but the information from the first image pulse is still on the register. The register takes ~30–80 ms to clear (depending on the type of CCD chip), during which time the electronic shutter remains open, and the photodiode array remains in a state where incident light from the flame is still recorded onto the camera detector. As a result, the second image is overexposed by the flame background luminosity, thus obscuring information from the particles or droplets. Our experience has shown that it is difficult, if not impossible, to utilize the conventionally available PIV systems for determining flowfield in high background spray flames.

In the system described here, the two cameras used allow one to measure flow velocity in three dimensions after proper calibration. The acquisition of a calibration image for the two-dimensional case is relatively straightforward. A target with evenly spaced high-contrast features is placed in front of the camera, and an image is acquired. The distances between the features are entered into the software, and the software allows one to relate camera pixels to distance in millimeters. However, the three-dimensional calibration is more complex. For three-dimensional data acquisition a series of at least five, and preferably nine, images each is acquired on the two cameras. Each image is recorded at some known distance from the known plane (centerline). The dimensions of one image are then entered into the software. The software observes the shift in the high-contrast features that results from each offset value and develops a complex relation that establishes a particle's motion in three-dimensional space on the basis of its travel between one PIV image and the next. The algorithm used to develop this relation is quite robust and tolerates a surprising amount of nonideality in target alignment, illumination, spacing, etc.

Each camera is equipped with a narrowband interference filter (centered at laser wavelength of 532 nm), which blocks off a majority of the background radiation produced by the flame other than this wavelength. Thus a filter alone cannot prevent overexposure of the photodiode in the camera because the light at the laser wavelength still enters the camera detector. The specific flame examined here was yellowish white and produced a very broad spectrum of distributed radiation. A sufficient portion of that radiation is in the 532-nm range, which transmits through the filter. The second image is therefore overexposed. To deal with this problem, a mechanical shutter, situated behind the camera optics and in front of the filter, is used. In operation the camera shutter begins to close at the initiation of each sample acquisition (first image). Therefore negligible light passes on to the camera detector after the second image acquisition because most of the light entering the cameras is during the significantly long time duration over which the register from the first image clears (~30–80 ms). The unwanted light passing onto the camera detector is thus eliminated. The second acquired image is thus of good and sharp quality. The mechanical shutter prevents overexposure of the photodiode array and makes it possible to carry out PIV analysis of luminous or high background radiation flames. This new operational cycle is described in Fig. 4. The resulting double images captured using mechanical shutters and narrowband interference filters are shown in Fig. 5. As can be seen, the second image is somewhat dimmer than the first because the shutter is already partly closed. However, there is no overexposure from background radiation from the flame. Thus the images obtained with the new PIV system allows one to make accurate and reliable PIV measurements in flames as the two recorded images of the particles and droplets are very sharp and clear. In cases where the flames are not as luminous or possess lower background radiation, the quality of the images obtained is much better than those obtained without any mechanical shutter and/or interference filters because the images obtained contain less noise with the result of more reliable and accurate information on mean velocity and turbulence characteristics.

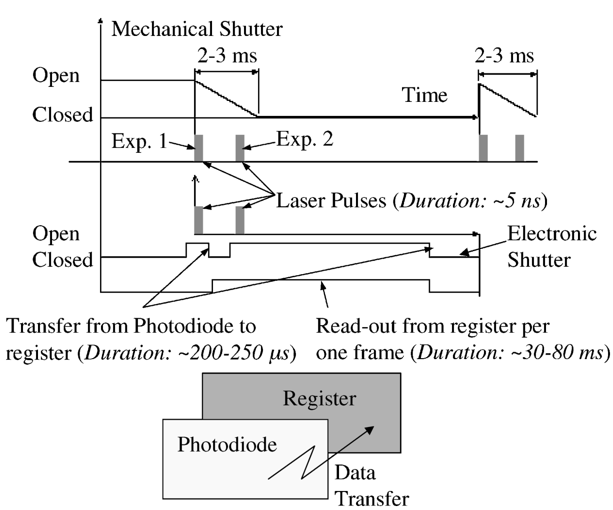
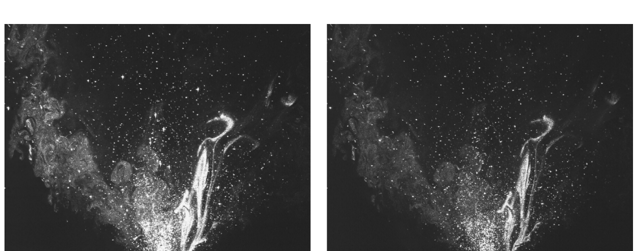


Fig. 4 Operational cycle of the new PIV system.



First Exposure Second Exposure

Fig. 5 Sample images from successive exposures using a mechanical shutter and narrowband filter.

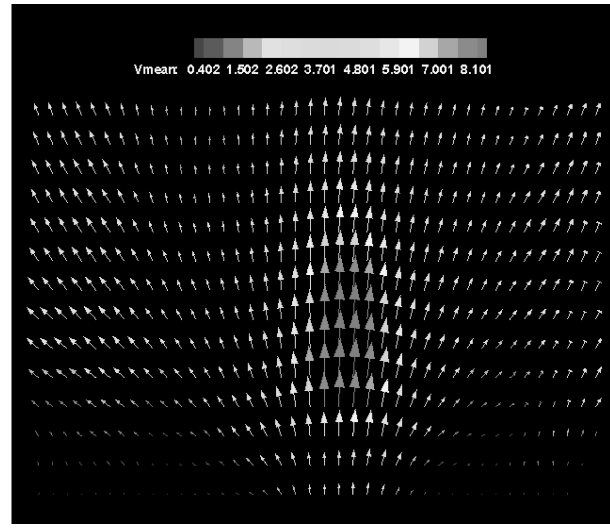


Fig. 6 Average three-dimensional velocity plot, color coded by axial velocity from within the luminous spray flame.

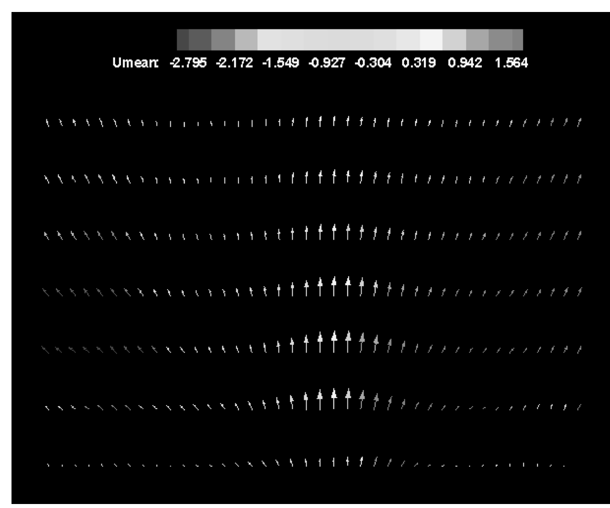


Fig. 7 Time-averaged radial velocity in the spray flame.

The data files generated by the PIV system are displayed and manipulated using the software. The software allows one to calculate mean and rms values of axial, radial, and tangential velocity. The information from the individual realization can also be used to calculate vorticity and strain rates and other flow characteristics. A comparison of the velocity information obtained from PIV with other diagnostics, such as phase Doppler interferometry technique, showed good agreement.

A sample flowfield average velocity vector plot from within a burning spray flame is shown in Fig. 6. The radial velocity distribution immediately downstream of the burner is shown in Fig. 7. The vector plots show the projection of the total three-dimensional velocity vector of the spray on the X-Y plane; the vectors are color coded according to the magnitude of the vector component of interest (axial velocity v or radial velocity u). The calculated vorticity distribution for the conditions just given is shown in Fig. 8. The results show low average vorticities, between -0.170 and 0.294, with the majority of the field near zero.

The data presented here have demonstrated the capability of the new PIV diagnostics to obtain measurements in any kind of combustion system including fuel sprays, solid fuel combustion, and other low or high background luminous flames. The diagnostic technique also allows one to obtain better quality data from flames with low or negligible background flame radiation. This type of data then allows one, **for the first time**, to make direct comparison between

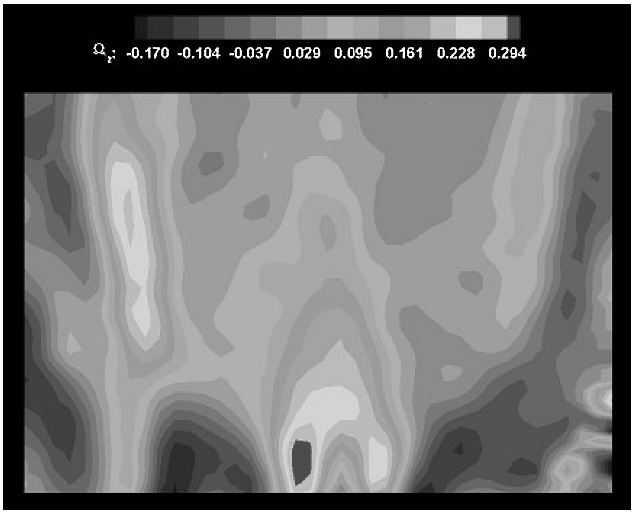


Fig. 8 Time-averaged vorticity map in the spray flame.

experimental data and predictions for the entire flow domain. The new PIV diagnostics also allow one to visualize the time resolved motion of the flow in three dimensions as a movie.

Conclusions

It has been demonstrated that the simultaneous use of mechanical shutter and narrow-bandpass interference filters can resolve overexposure problems associated with PIV diagnostics in flames, in particular luminous flames that feature high background flame radiation. The PIV system discussed here is capable of detecting fuel droplets, particles, or seed particles under a variety of flow conditions. The diagnostics allow one for the first time to obtain detailed and comprehensive information on flow dynamics associated with complex flows, including swirling flows, jets, and various kinds of practical systems under reacting and combustion conditions can be generated.

Acknowledgment

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Reaction Rates for Hypergolic Propellants Using Chemical Delay Times

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Introduction

HYPERGOLIC bipropellants are defined as fuel and oxidizer combinations that, upon contact, chemically react and release enough heat to spontaneously ignite. Nitric acid and oxides of nitrogen are used as the oxidizer. The fuels are organic compounds including amines, heterocyclic compounds, and polyatomic phenols.

The discovery of hypergolicity occurred in Germany around 1937, and research on hypergolic bipropellant combinations spread to other countries after WWII.[1] During the 1950s, interest in hypergolic combinations grew as knowledge of their high density, high performance, and long-term storability developed. The Titan, Gemini, and Apollo programs all used hypergolic propellants. Currently the Ariane, Long March, Space Shuttle, and International Space Station programs are among the most recognizable users of hypergols.

One important measure of the hypergolic performance is the length of time between reactant contact and appearance of the flame, termed the ignition delay time (IDT). Measured in milliseconds, IDT is important because longer than desired delays can lead to lower performance or cause catastrophic failure of the engine.

This Note reports on a new laser diagnostic method to measure and examine ignition delays for hypergolic reactions. This technique, as a result of its time resolution, is the first to measure the chemical delay time (CDT) just prior to ignition. This new chemical performance measurement can be used to compare hypergolic reactions and defines the time during which free radicals generated by the reactions should be analyzed.

Equipment

The entire operating system is designed to study the reaction rates and mechanisms of hypergolic reactants for the ability to propose alternate mechanisms. The equipment uses a variety of techniques, including visible and near-infrared Raman spectroscopic measurements, to meet these objectives. The combustion chamber, supporting systems, and diagnostics have been designed and assembled as illustrated in Fig. 1. The operating system is described in detail in previous publications.[2–5]

Currently, the combustion system supports ignition and CDT studies between liquid fuel and oxidizer. Modifications can be made to study other reactive systems such as solid fuels and gelled propellants. Therefore, a wide variety of hypergolic systems can be kinetically studied in a controlled environment leading to an understanding of the mechanisms and free radicals, which control these reactions.

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