A PLANAR-FLUORESCENCE IMAGING TECHNIQUE FOR STUDYING DROPLET-TURBULENCE INTERACTIONS IN VAPORIZING SPRAYS*

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ABSTRACT

Droplet-turbulence interactions directly affect the vaporization and dispersion of droplets in liquid sprays and therefore play a major role in fuel-oxidizer mixing in liquid fueled combustion systems. Proper characterization of droplet-turbulence interactions in vaporizing sprays requires measurement of droplet size-velocity and size-temperature correlations. This paper describes a planar, fluorescence imaging technique which is being developed for simultaneously measuring the size, velocity and temperature of individual droplets in vaporizing sprays. Preliminary droplet size-velocity correlation measurements made with this technique are presented. These measurements are also compared to and show very good agreement with measurements made in the same spray using a phase-doppler particle analyzer.

INTRODUCTION

The performance of liquid fueled combustion systems is significantly affected by the characteristics of the liquid fuel (and/or oxidizer) spray. In order to understand the underlying fundamental processes which determine the characteristics of liquid sprays, typical of those used in liquid rocket, Diesel and gas turbine combustors, it is useful to divide such sprays into three different regimes: an atomization regime, a dense spray regime and a dilute spray regime. The atomization regime refers to the region of the spray where droplets are formed due to unstable wave growth on the surface of the injected liquid. The size of the droplets produced by the atomization process depends on the relative velocity of the injected liquid, the liquid surface tension and the gas density[1,2].

The dense spray regime refers to regions of the spray where droplets strongly interact and extends from the surface of the injected liquid to regions of the spray where the droplet spacing to diameter ratio is anywhere from ~3 to ~10, depending on the criterion used to define the dense spray regime. One common criterion relates to the optical density of the spray, where regions of the spray which are so dense as to be optically opaque, and therefore inaccessible to optical measurement techniques, are considered to be in the dense spray regime. Because dense regions of the spray are optically inaccessible, very little is actually known from direct observation about the atomization process and droplet interactions. Valuable insights have been obtained, however, from detailed spray models[3-6] which have been successful at predicting many of the measurable properties of sprays such as drop velocity and size in the downstream dilute regions of the spray. For example, calculations have shown that droplet collisions and coalescence are important processes in the dense regions of the spray, causing the droplet size to actually increase.

The dilute spray regime generally refers to regions of the spray where droplet collisions are negligible and extends from the dense regions of the spray to the outermost boundaries of the spray. Since dilute sprays are optically accessible, there have been a number of experimental studies characterizing droplet velocity and size in the dilute regions of liquid sprays[6-12]. It is in the dilute regions of the spray where there is considerable interaction between the droplets and the surrounding turbulent gas which is entrained into the spray. This interaction is responsible for the heating, vaporization and deceleration or acceleration of the droplets, i.e. the transport of energy, mass, and momentum between the droplets and the surrounding turbulent gas, and therefore to a great extent determines the fuel-oxidizer mixing characteristics of the spray. It is also important to note that even though the droplets do not collide, they do interact, in that individual droplets lie within the wakes of nearby droplets which can affect droplet drag and vaporization[13].

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In order to properly account for the effects of turbulence in vaporizing sprays, the intensity, scale and energy spectrum of the turbulence must all be considered. This is necessary, because different turbulence scales affect the spray in different ways and therefore the energy distribution over the range of turbulence scales must be known. For example, small scale turbulence, i.e. of the order of the droplet spacing and diameter, enhances the small scale mixing necessary to achieve local premixed conditions, as well as, the drag and vaporization of the droplets. Whereas large scale turbulence, i.e. of the order of the overall spray diameter, is most effective at dispersing the droplets and producing large scale entrainment of gas, liquid vapor and liquid droplets. In general, the regions of the spray where one would expect droplet-turbulence interactions to be most important are the outer edges and downstream regions of the spray as shown in Figure 1.

In order to study droplet-turbulence interactions in vaporizing sprays, one would like to isolate those regions of the spray where the mass, momentum and energy exchange between droplets and gas is greatest and then systematically and independently vary the relevant parameters such as the droplet size, density, velocity and temperature, as well as, the gas velocity, temperature and turbulence. It is also necessary to measure the changes in these parameters as the droplets and gas interact. Such a systematic study is difficult to do in an actual spray because of the interdependent nature of the spray properties. Therefore, rather than use an actual spray, the effects of turbulence on vaporizing sprays can be studied in a spray configuration designed to simulate one particular portion of an actual liquid spray having a given droplet number density and droplet size, velocity and temperature distribution, as well as, given gas temperature, pressure and turbulence properties.

Such experiments are being conducted in a turbulent flow system[14], illustrated in Figure 2, which is capable of simulating the range of turbulent flow conditions encountered in the peripheral and downstream regions of a liquid spray. Turbulence is generated using a turbulence generator which is capable of producing turbulent flows which are uniform over the cross-section of the test section to within ± 10%, with relative turbulence intensities up to 70%, and mean velocities up to 30 m/sec. With this turbulent flow system it is possible to independently vary the mean velocity and the turbulence properties in order to distinguish between and characterize their effects on droplet heating, vaporization and dispersion, and in turn on fuel-oxidizer mixing.

The spray is produced with a pressure atomizer (Delavan WDB 6.00-30°), where a 10mm diameter skimmer is used to isolate the central core of the spray before it is transversely injected into the turbulent flow, as illustrated in Figure 3. Only the central core of the spray is used in order to achieve relatively uniform spray properties, i.e. size and velocity distributions and number density, across the spray diameter at the point where it enters the turbulent flow. By changing the spray nozzle, the injection pressure, and the nozzle to skimmer distance, it is possible to vary the droplet size distribution, velocity distribution and number density over a range of values representative of those encountered in the peripheral and downstream regions of a liquid spray where fuel-oxidizer mixing occurs. An optically accessible, one atmosphere, 300K version of this flow system and spray skimmer assembly has been used for the development and testing of the planar-fluorescence droplet imaging technique described below.

In order to properly characterize droplet-turbulence interactions and their effect on fuel-oxidizer mixing in vaporizing sprays, it is necessary to measure various droplet, liquid vapor and gas properties. Specifically, this includes droplet size, number density, velocity and temperature; liquid vapor concentration; and gas velocity, turbulence intensity, scale and energy spectrum. To date there have been a number of studies in dilute vaporizing sprays where droplet velocity[8,9,11,12], gas velocity[9] and droplet size have been measured[9,10,12]. It is important to note, however, that since droplet-turbulence interactions, e.g. droplet drag and vaporization, are dependent on droplet size, it is necessary to simultaneously measure the velocity and size and the temperature and size of individual droplets in order to understand and properly account for these interactions.

There are a number of techniques which have been developed and used for droplet velocity, size and temperature measures. However, in order to obtain velocity-size or temperature-size correlations, only those techniques which make measurements on individual droplets can be used. Techniques which have been successfully used to measure individual droplet velocities in sprays include laser doppler velocimetry and droplet imaging velocimetry. Techniques which have been successfully used to measure the size of individual droplets in sprays include phase-doppler and pulse-height techniques, as well as, droplet imaging. Both phase-doppler and pulse-height droplet sizing techniques have been combined with laser doppler velocimetry in order to make simultaneous droplet velocity and size measurements in sprays. The so-called phase-doppler particle analyzer is the most widely used approach, having been used to measure droplet size and velocity in a number of spray studies. Results obtained with the phase-doppler system for droplet velocity and droplet size distributions have been shown to be reasonably accurate and reliable, however, measurements of volume flux and therefore the velocity-size correlation are less certain[12,15,16]. With respect to studying droplet-turbulence interactions in vaporizing sprays, a current limitation of these techniques, is the fact that they can not be used to obtain individual droplet temperature measurements. (It may be possible to use the temperature dependence of the index of refraction of the liquid droplet to measure its temperature in combination with the phase-doppler technique[17]). There are few techniques which have been developed for measuring individual droplet temperatures in vaporizing sprays. One technique which has been proposed for droplet temperature measurements is based on the use of exciplex fluorescence[18]. This technique exploits the photophysics of organic exciplexes. The liquid is doped with a molecule, referred to as the monomer, which is capable of forming an excited state complex or exciplex. When the solution is exposed to ultraviolet radiation, the monomer and exciplex emit visible fluorescence at two different wavelengths. Since the relative concentration of the monomer and the exciplex is temperature dependent, the resultant ratio of the monomer to exciplex fluorescence is a measure of the liquid temperature. There are a number of concerns regarding the use of this technique for measuring individual droplet temperatures in vaporizing sprays including the effect of oxygen quenching and the question of whether the surface or internal droplet temperature is measured. Work is in progress at a number of laboratories to resolve these issues. One method of measuring the relative intensity of the monomer and exciplex fluorescence is to record simultaneous droplet images at both the monomer and exciplex fluorescence wavelengths. Such a measurement can easily be combined with droplet imaging velocimetry and sizing to make simultaneous droplet size, velocity and temperature measurements. This is the objective of the current program. In this paper the status of the simultaneous droplet size and velocity measurement technique is presented.

EXPERIMENTAL TECHNIQUE

Imaging based methods have been used by other researchers to obtain droplet size and droplet velocity measurements[19,20]. These systems have typically employed backlighting to form the image. Using this approach the sample volume is controlled by the depth of field of the imaging optics, and therefore droplets which are adjacent to the sample volume are out of focus and have ambiguous diameters. These droplets must either be eliminated from the distribution or the diameters must be corrected using some criteria. Other limitations when using backlighting pertain to the type of light source used. With a white light source it can be difficult to achieve the high intensity, short duration (e.g. nanosecond) light pulses necessary to accurately image small (e.g. 10 micron diameter), high velocity (e.g. 100 m/sec) droplets. This can be accomplished with a pulsed laser, however it then becomes difficult to accurately size small droplets due to the appearance of diffraction rings surrounding the droplet image. A method of illuminating and imaging droplets which does not have these problems involves doping the liquid with a fluorescing dye and illuminating a "two-dimensional slice" of the spray with a thin sheet of laser light which excites the dye and causes the droplets which lie within the laser sheet to fluoresce. The fluorescing droplets are then imaged at ninety degrees, where the spatial resolution is determined by the thickness of the laser sheet and the resolution of the recording medium. The droplet size is determined directly from the droplet image. To obtain the droplet velocity, the laser can be double-pulsed, where the resultant displacement of the droplet image is then used to determine two components of the droplet velocity. As the droplet number density increases, however, it becomes difficult to identify the correct droplet-pairs. One way to partially solve this problem is to use light pulses of different intensity or duration. This also allows the sense of the droplets motion to be determined. A similar approach can be used with the planar fluorescence imaging technique, which involves doping the liquid with two dyes that absorb at different and fluoresce at different wavelengths. The two color method reduces the ambiguity in the selection of the correct droplet pairs and allows the image processing to be automated. Automation permits greatly increased sample sizes which are crucial for accurate determinations of the droplet distribution functions. A schematic drawing of the planar fluorescence droplet imaging system is shown in Figure 4.

For the measurements reported in this paper, the injected liquid (methanol) was doped with two fluorescent dyes. The dyes employed were Rhodamine-610 and N,N,N',N'-Tetramethyl-1,4-phenylenediamine (TMPD). The absorption and emission bands of these dyes are spectrally separated for each dye as well as one dye from the other, and they can both be readily excited with a Nd:YAG laser, i.e. Rhodamine 610 absorbs at the second harmonic of the Nd:YAG (532nm) and fluoresces at ~610nm, while TMPD absorbs at the third harmonic of the Nd:YAG (355 nm) and fluoresces at ~400nm. (As noted above, TMPD can also form an exciplex which will fluoresce at ~500nm). The interval between the two pulses was 30 microseconds. Selection of the optimum interval requires an a priori estimate of the droplet velocity. The beams were focused into sheets using the combination of a convex cylindrical lens and a convex spherical lens. The laser sheet thickness over the field of view of the measurement was less than 0.4mm. The droplet images were recorded on color slide film (ASA 400) at a magnification ratio of 2:1. Residual light from the second harmonic was blocked before entering the imaging optics with a narrowband interference mirror. The slide film was not sensitive to residual light from the third harmonic so there was no need to eliminate it. The resultant image recorded on the film consisted of a red image and a blue image from each droplet which passed through the plane of the laser sheets. There was also the possibility that a droplet was entering or leaving the laser sheet in which case only one droplet image appeared. This was the case for twenty percent of the droplets under the conditions reported in this paper. Another problem which was encountered was that the red images were subject to significant spreading during the developing process (up to 40% larger than the blue images). Therefore, the blue images were used for sizing and the red images were only used for establishing the distance travelled.

An automated image processing system was developed to extract the droplet velocity and size from the slides. The slide was backlit with a white light and either a red or blue bandpass filter was interposed between the lamp and the slide. Only the images at the wavelength of the filter were visible, therefore the red and blue droplet images could be analyzed separately. A 2mmx1.2mm section of the slide (referred to as the interrogation spot) was imaged onto a 512x480 array video camera, yielding a theoretical measurement resolution of 2.9 microns in the vertical direction and 2.4 microns in the horizontal direction. (The actual resolution is greater than this due to diffraction effects.) The image was scanned and the size and location of each droplet was recorded. The criterion used for locating the endpoints of a droplet diameter was the location of largest positive and largest negative slope in the intensity profile. The procedure was repeated at the second wavelength, resulting in a database of size and position for each of the individual blue and red droplet images.

In any given interrogation spot, from 5 to 10 droplet pairs and several more single droplets were visible. The procedure for matching the red images to the blue images was as follows. First, all the red drops with diameters within +40%, -10% of a blue droplet were selected. This was repeated for each blue droplet. A given red droplet might appear as a possible match for more than one blue droplet. In that case the program selected the droplet pairs which minimized the separation distance squared. This criteria was based on the assumption that droplets of the same size in close proximity in the flow could be expected to have highly correlated velocities. This assumption was supported by visually inspecting the data slides. Once the proper droplet pairs were identified, the droplet displacement, and therefore velocity, was determined.

PRELIMINARY RESULTS

The automated image processing system was based on of a 25 MHz, 386 personal computer which also controlled the stepping motor system which automatically traversed through the entire slide and controlled the image recording and processing software which determined the droplet position, size and velocity. With this system it was possible to process an entire 35mm slide which includes up to 400 droplet pairs in approximately one hour.

Preliminary droplet size and velocity measurements obtained with the planar fluorescence imaging technique are given in Figures 5 and 6 where the size distribution and velocity distribution, respectively, are plotted. These measurements were made in the flow system and spray-skimmer assembly described in the previous section under conditions of no gas flow. The measurement location was at the exit of the skimmer assembly and the field of view corresponded to a 10mm x10mm section of the spray.

The droplet size and velocity distributions are consistent with what was expected for the spray nozzle which was used. The distributions will become smoother as the sample size, N, is increased. The droplet size-velocity correlation shows that there is a shift toward higher velocities as the droplet size increases, as would be expected due to the greater momentum of the larger droplets. Note that the planar fluorescence imaging also gives the droplet number density, which for this spray condition is nearly 10^4 droplets/cm^3.

Measurements were also made under the same conditions using an Aerometrics phase-doppler particle analyzer. A comparison between the results obtained with these two techniques is given in Table 1. This comparison shows very good agreement between the two measurement techniques, however, it should be noted that this is only based on a comparison of mean spray properties. It should also be noted that to properly compare the results obtained using these two techniques, it is necessary to account for the fact that planar fluorescence droplet imaging gives a spatial average and phase-doppler gives a temporal average. Additional measurements and a more detailed comparison of these two techniques are in progress.

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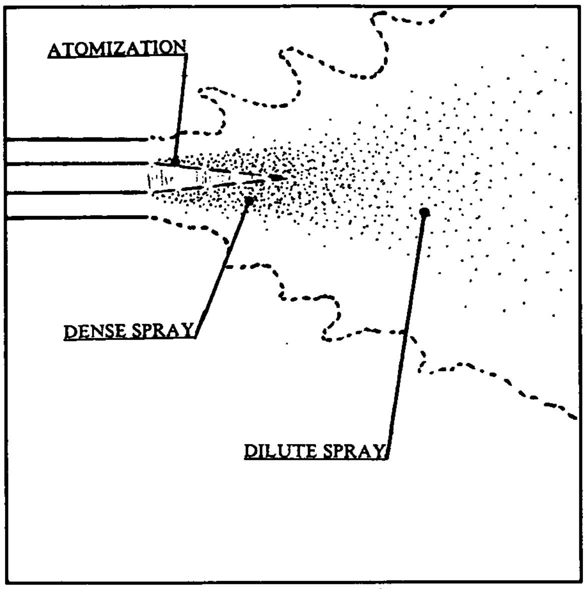

Figure 1: Spray Regimes

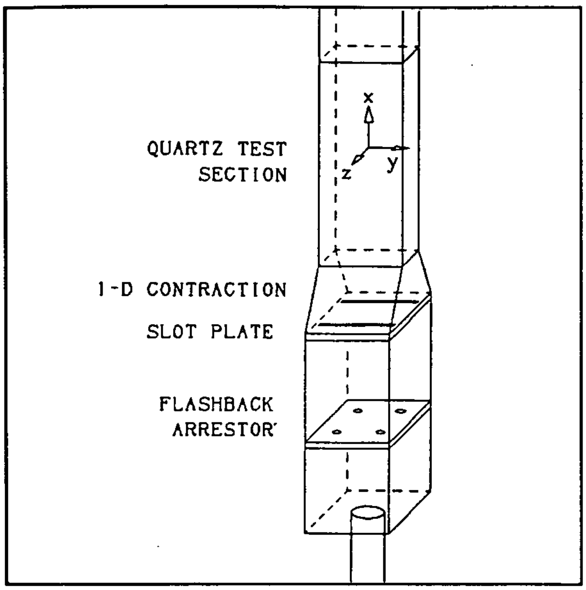

Figure 2: Turbulent Flow System

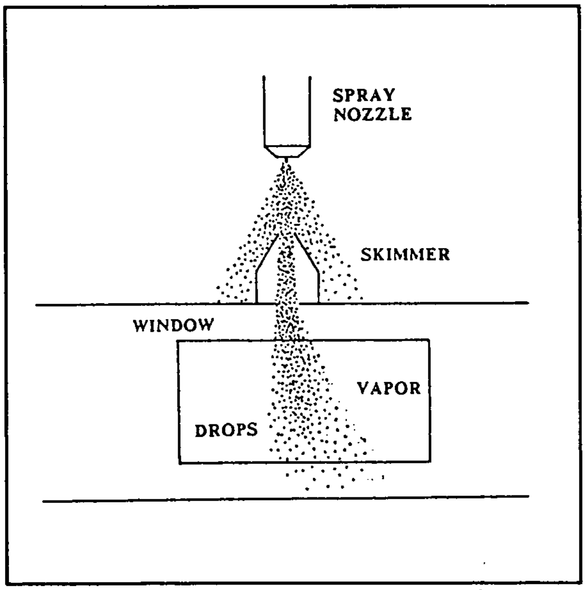

Figure 3: Spray-Skimmer Assembly

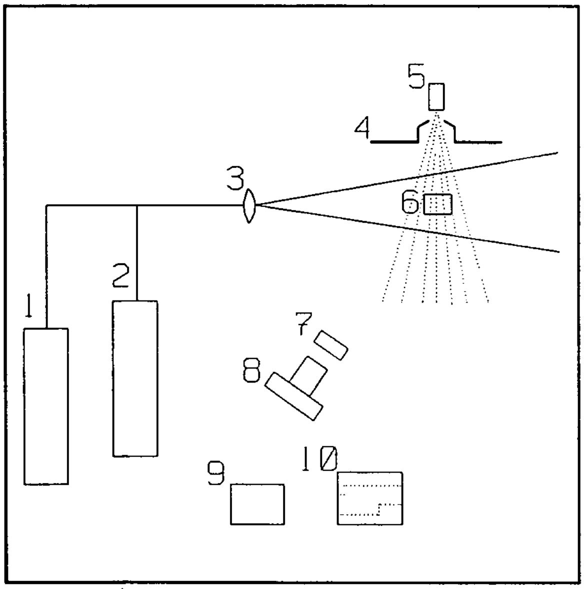

Figure 4: Experimental Apparatus. 1-355nm beam, 532nm beam, 3-light sheet optics, 4-skimmer, 5-nozzle, 6-sample volume, 7-532nm mirror, 8-35mm camera, 9-laser trigger, 10-oscilloscope.

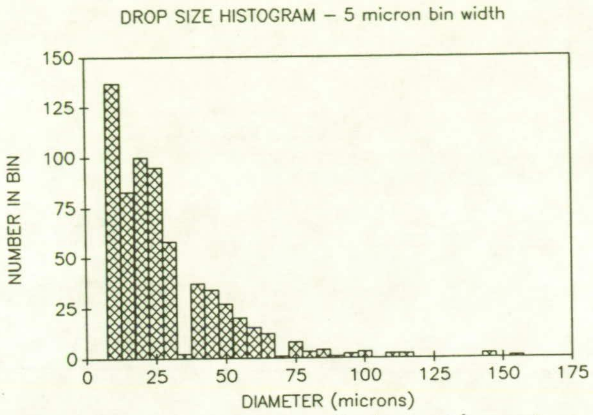

Figure 5: Droplet Diameter Histogram

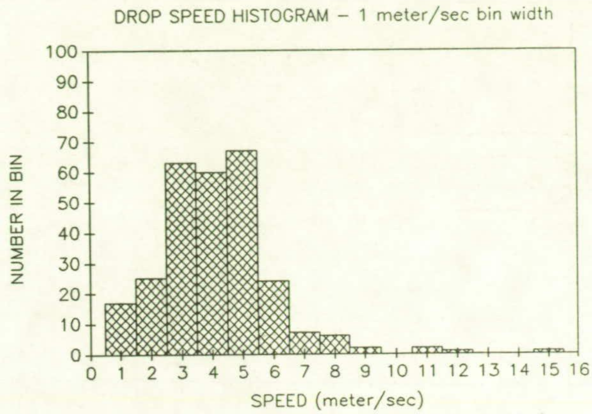

Figure 6: Droplet Velocity Histogram

Table I: Comparison Between Planar Fluorescence and Phase-Doppler Measurements

	PLANAR FLUORESCENCE	PHASE DOPPLER
D10	30 um	24 um
D20	37 um	31 um
D30	44 um	38 um
D32	62 um	54 um
Vav	4.2 m/s	4.8 m/s
N	650	8007