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Combined PDA/LIF Measurements in Simple, Evaporating Turbulent Spray Jets

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Abstract

This paper is part of a continuing study aimed at investigating the structure of non-reacting and reacting turbulent spray flows. A simple jet nozzle is used to produce a slender shear flow in a co-flowing air stream with well-defined initial and boundary conditions. The flow is made intentionally simple and relatively easy to model so that the focus can be on the important aspects of droplet evaporation rates and turbulence-droplet interactions. Acetone spray in air is used here for convenience of diagnostics. The phase-Doppler anemometry (PDA) technique is employed to record droplet quantities while laser-induced fluorescence (LIF) imaging is applied separately to obtain acetone vapour data.

The combined liquid and vapour mass fluxes of acetone measured at various axial locations in the jet agree satisfactorily with the total mass flow rate of acetone injected. As expected, the mean slip velocity increases for larger droplets and is found an important quantity for the overall evaporation of sprays. The evaporation rate increases significantly with decreasing Sauter mean diameter of droplets. More research is needed to quantify these effects resulting in an improved droplet evaporation model.

Introduction

The physics and chemistry of spray flows in industrial applications, ranging from food processing to burners and internal combustion engines, are made more complex by the largely unknown interactions between the droplets, the turbulence and the chemical processes involved. Detailed measurements are scarce, and the capabilities of numerical codes are limited by the empiricism in the physical sub models used for droplet evaporation, combustion and turbulence. In the experiments presented here we aim to minimize these complexities by using a spray nozzle designed to avoid some of the modelling difficulties often encountered in the near field (high initial velocity, recirculation, steep axial gradients and non-uniform distribution). A carrier air stream advects the spray from a nebulizer through an orifice, at the exit of which the droplet distribution is fairly uniform and optical and hardware probe access is good. Similar designs are also employed by others [4,5]. However, our nozzle is also externally tapered and placed at the exit plane of a wind tunnel in a filtered co-flowing air stream to avoid axial pressure gradients and ambient disturbances, and to enable Rayleigh measurements to be made. In the combusting version an annular premixed pilot flame anchors the spray flame on the thin burner lip. (This is an extension of studies in this laboratory on turbulence-chemistry interactions in piloted jet flames [3]). Here we have a simple, slender shear flow for which gradient models are known to work well. A volatile acetone spray is used to emphasize evaporation aspects.

Mass flux measurements by PDA alone are notoriously difficult and unreliable [6]. Commonly, less than one half of the droplet flux is captured by commercial instruments even in simple flows. Therefore, a combination of PDA and LIF scattering measurements is employed primarily to enable a check on the performance of the PDA equipment in a cold spray, before its performance in more difficult flame measurements can be relied upon.

Experimental

The spray nozzle in Figure 1 is mounted in a 3 m/s co-flowing air stream with less than 2 per cent turbulence intensity. The main fuel tube is 75 mm long and has an inner diameter of 9.8 mm. There is no back-flow of liquid into the bottom of the nozzle. Pressurized liquid acetone is fed into the nebulizer and its flow rate is measured, like the other flow rates, by rotameters.

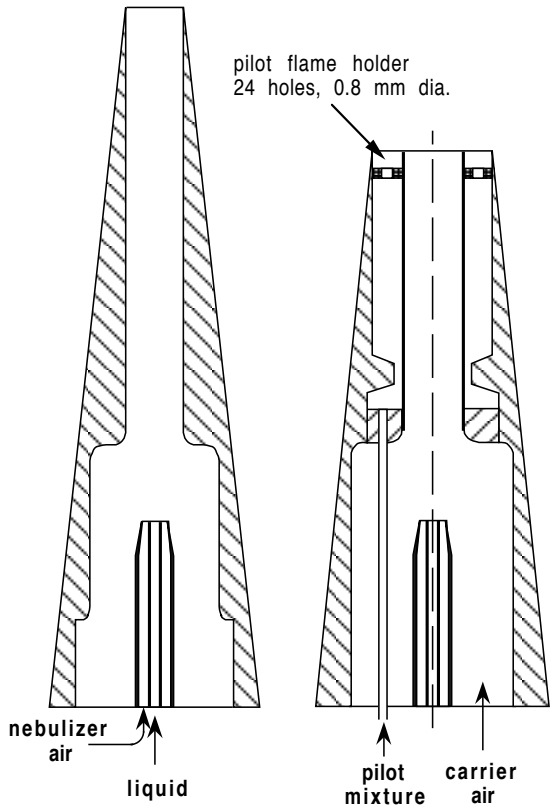

Figure 1. Spray jet nozzle (left) and burner design.

The PDA instrument (Aerometrics model 3200) is arranged in 45 degree forward scattering, with 300 mm receiver focal length and 3 micron fringe spacing. A 7W argon-ion laser feeds the fiber-optics assembly. The power in each beam at the measurement volume is 50 - 100 mW. Photomultiplier voltages are set at 350 - 400 V. Two components of velocity are recorded. Software correction is made for the lower visibility of small droplets at the edge of the measurement volume.

LIF images of the vapour (including droplets) are produced by forming a 6-mm high sheet from the 266 nm quadrupled output of a pulsed Nd:YAG laser, and capturing the images at 90 degrees to the sheet plane. An unintensified 12-bit CCD camera is used to maximize resolution and dynamic range.

The camera lens is opaque to UV radiation, so that only the fluorescence is recorded. Each pixel represents 18.8 microns in the image plane. To calibrate the images, a vapour/air mixture of constant composition is produced by bubbling air through acetone liquid; the acetone number density in this mixture is determined by Rayleigh scattering, relative to air. Images of the mixture are then used to calibrate the jet flow. Beam attenuation, quenching, and fluorescence trapping are found to be insignificant in this dilute flow. The incident UV beam intensity has been kept constant within 5 percent. Averages of 30 images are used.

To obtain vapour data only, it is necessary to remove the LIF trace of the droplets. They are easily identified by their high gradients and are removed by digital filtering. The 'holes' left are filled by the average of the immediate surroundings. There are two potential sources of error in this approach. First, optical wakes behind the droplets must exist and have been studied by others [2]. Such wakes would reduce the vapour fluorescence intensity. However, they are completely undetectable in this spray, most likely due to our using high laser beam fluence and an incident wavelength of much lower fluorescence yield than that in [2]. Secondly, droplets below 3 microns may go undetected, as indicated by a comparison of number density in the images with the PDA data. However, these droplets contain less than one percent of the total droplet mass, and so do not contribute significantly by being double-counted in the overall acetone flux, assuming they are also counted in the PDA data.

When calculating the axial fluxes, we have chosen for simplicity to neglect the contribution of turbulent fluxes. The effect of this omission is estimated, following Antonia *et al.* [1] to reduce fluxes by two to four per cent. Also, the error due to gas density increase incurred by droplet cooling during the evaporation is estimated to be negligible.

Results have been obtained for four cases, as shown in Table I. The flow rate of carrier air is changed between high and low velocity. The liquid acetone injection rates are adjusted for sparse and dense seeding. The total mass loading of acetone in the main jet ranges from 0.026 to 0.051. The volume-averaged mean diameter, D_{30}, is also varied by altering the nebulizer air pressure for fine and coarse droplets.

CASE	LFS	HFS	HFD	HCS
Jet Reynolds number	15,300	30,000	30,000	30,000
Liquid inj. rate, g/min	7.03	7.03	11.7	7.03
D_{30} at nozzle exit, μm	9.3	12.0	13.4	17.1

Table 1. Experimental conditions.

Results and Discussion

In what follows, the focus is mainly on case HFS for high velocity, fine droplet and sparse seeding. This case is found to represent general trends of the sprays investigated. Unless otherwise indicated, this is the case shown in the figures.

Statistics of the droplet distribution is shown in the form of volume-averaged droplet diameter, D_{30}, in Figure 2 and probability density function (pdf) plots in Figure 3. On the jet axis, D_{30} increases with x/D (the distance from the nozzle normalized by the nozzle diameter, D = 9.8 mm) and decreases radially towards the edge of the jet, as also found previously [7]. The probability density functions of droplet diameter in Figure 3 show the same trend.

At x/D = 5 and 10, the 'kink' in the radial profiles of D_{30} is thought to be an instrument artefact. In order to match velocity changes, it is necessary to change the rate at which the Doppler bursts are sampled at these loci, and this is known to alter the relative visibility of large and small droplets. (This also somewhat affects the corresponding droplet velocity data, as seen in Figure 6 at x/D = 15.) At x/D = 20 and 25, where no sampling rate change is needed, the profiles are smooth.

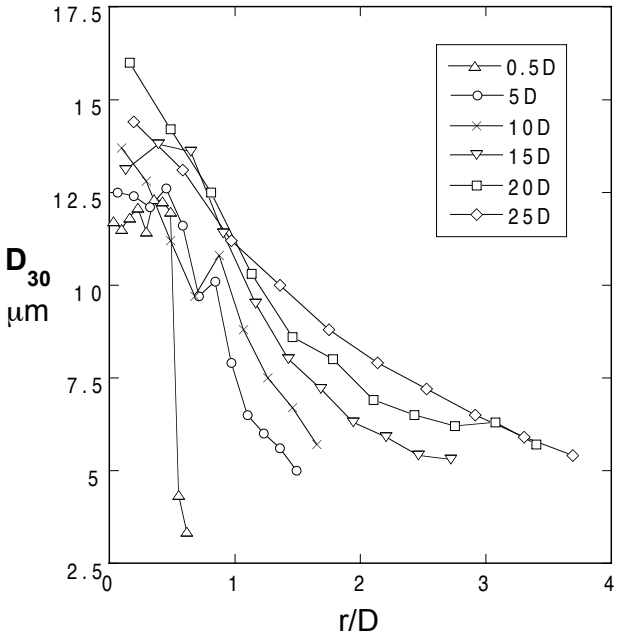

Figure 2. Radial profiles of droplet volume-averaged mean diameter, D_{30}, at 0.5 to 25 nozzle diameters from the jet exit.

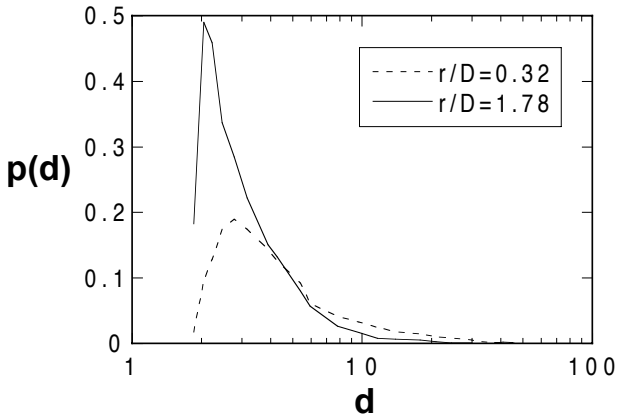

Figure 3. Probability density, p(d), of droplet diameter, d, at x/D = 20 near the axis and in the outer shear layer.

Evaporation is a vital feature in spray jets. A measure of the bulk evaporation rate is obtained here by integration of the droplet mass flux across the jet at all axial locations. Figure 4 shows these integrated fluxes normalized by the total injected flux for all four measured cases. The flight time, t, at a given axial location is obtained by integrating along the axis one over the centreline mean axial velocity conditioned for droplets less than 3 μm. The inlet of the fuel tube, 75 mm upstream of the nozzle exit, is set to t = 0. The time domain, rather than x/D, is used here to remove the residence time effect: the high velocity sprays have less time for evaporation than the low velocity spray at the same axial location.

It is readily seen that a fine spray (HFS) evaporates more rapidly than a coarse spray (HCS). For cases HFS and LFS of the same liquid injection rate at t = 0, lower turbulence intensity

and lower slip velocity are found for the low velocity case of LFS at all the axial locations. Both effects suggest that LFS would have lower evaporation rates than HFS. This cannot explain the anomaly that lower droplet flux is found for LFS than HFS at downstream locations of the same flight time.

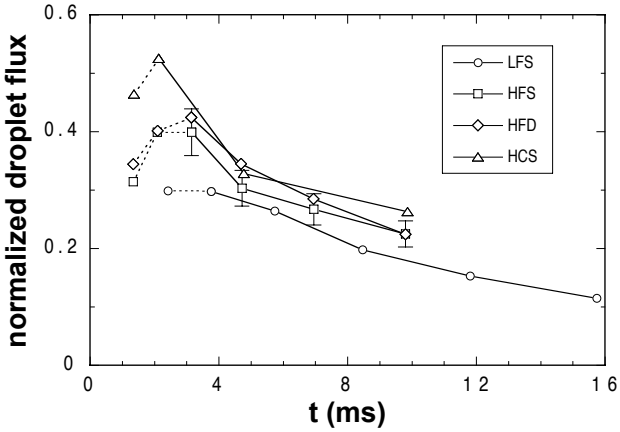

Figure 4. Droplet mass flux integrated across the jet.

It is also clear in Figure 4 that the integrated droplet fluxes measured near the nozzle exit (shown in dashed lines) must be in error, as they should increase with decreasing t (or x/D) and should be unity at t = 0. This is confirmed when the vapour flux, integrated the same way, is added to the droplet flux in Figure 5. This sum represents the total flux, a conserved scalar. An uncertainty of 10% for the downstream droplet flux can also be inferred from Figure 5 and is shown in error bars in Figure 4 for case HFS. The recorded nozzle droplet flux is most in error for case HFD (as also reported in the preliminary work on this spray [7]). This spray has the highest number density and the arrival rate near the nozzle exit, and the PDA equipment is unable to record all the droplet arrivals. This finding is important for measurements that have been made in turbulent flames on the same occasion, where the adequacy of the PDA instrument for droplet flux measurements cannot be similarly tested.

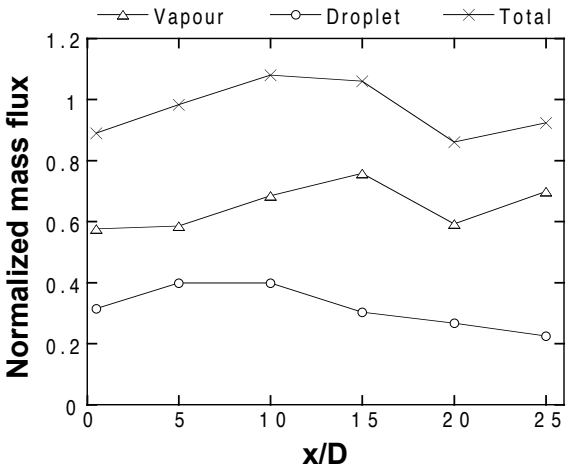

Figure 5. Acetone mass fluxes, integrated across the jet, and normalized by the acetone injection flux for case HFS.

The mean axial velocities conditioned on droplets of diameters less than 5 μm are shown in Figure 6. Size discrimination is used here to approximate to the gas velocity. The anomalous shapes at x/D = 10 and 15 have been discussed in the context of Figure 2.

The mean slip velocity is of particular importance in any evaporating spray, and is readily accessible here. To gauge whether realistic slip velocities are obtained, the centreline decay of droplet velocity, U_d, is plotted in Figure 7, conditional on size. We would expect large droplets initially to be accelerated in the 75 mm long nozzle, emerge at somewhat less than the mean gas velocity, U_g, and then during the deceleration in the jet increasingly develop a positive mean slip velocity. This is indeed what is seen in Figure 7, where particles in the d < 3 μm size range are assumed to approximate to U_g. It can also be seen that U_d in the range 10 - 30 μm closely approximates to the d < 90 μm range, *i.e.*, all droplets.

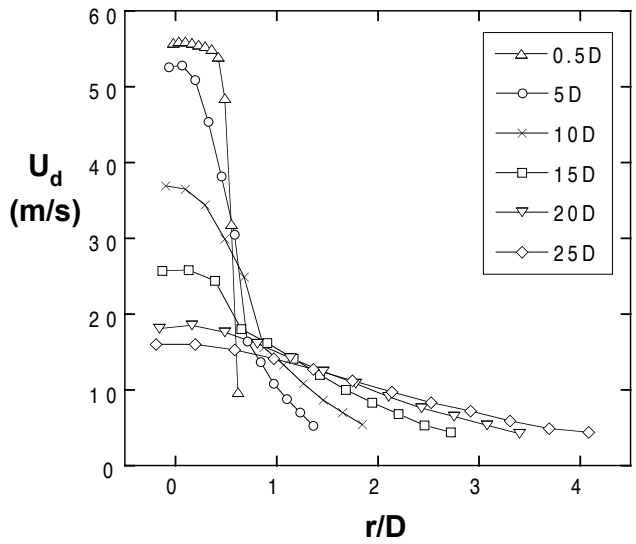

Figure 6. Radial profiles of mean droplet velocity, U_d (d < 5 μm).

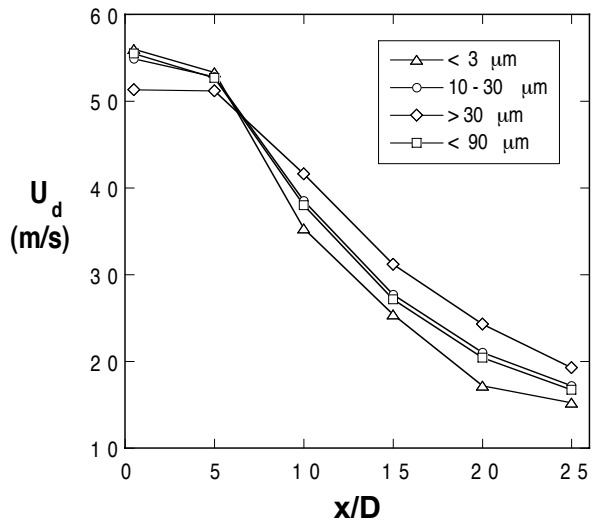

Figure 7. Centreline decay of mean droplet velocity, conditioned on the droplet size.

At downstream locations where the spray decelerates, the largest slip velocity would be expected to occur for the largest droplets. This can be best viewed from the scatter plot between droplet velocity and diameter. Figure 8 shows one such scatter plot at the jet centreline and x/D = 20. A positive correlation between droplet velocity and diameter can be clearly inferred. If the small droplets of d < 3 μm are taken to follow the gas flow faithfully, the mean slip velocity can be approximated to scale linearly with the mean droplet size for the range of droplet sizes measured. On the other hand, a negative

correlation is observed near the burner exit (x/D < 5). This is attributed to the fact that larger droplets do not follow the gas flow as readily as smaller ones. For the current spray jets, droplets of size greater than 3 μm may already have substantial slip velocities with the surrounding gas as is discussed below.

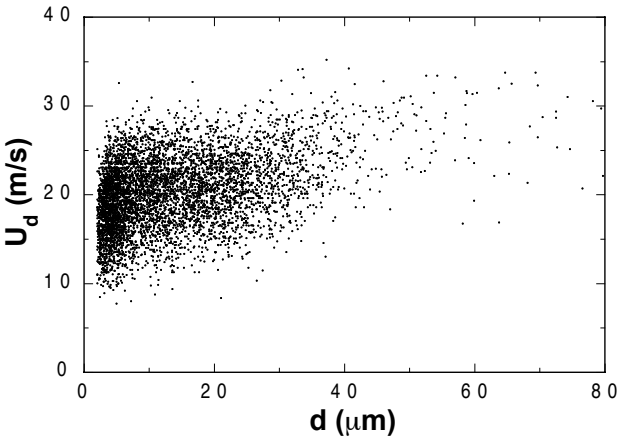

Figure 8. Scatter plot of the droplet velocity versus droplet diameter, at the jet centreline and x/D = 20.

In Figure 9 radial profiles of the mean droplet velocity are plotted for several size ranges, at x/D = 20. The most obvious feature is that large droplets can travel more than 7 m/s faster than U_g, even this far downstream. Also, even when all droplets above 5 μm are excluded, indications are that U_d is still significantly above U_g. There is almost a 10 per cent decrease in U_d as the size is lowered further to 3 μm (the limit for statistically significant samples to be obtained here). These results obviously depend on the efficacy with which the PDA instrument classifies the droplets, an aspect not directly verifiable. A poor classification would bring the profiles for large and small droplets closer together. Hence, we can assume that the spacing between the profiles in Figure 7 is not exaggerated but may in fact be understated.

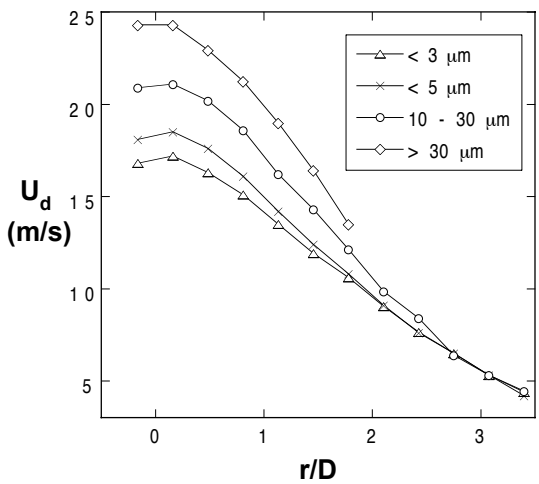

Figure 9. Radial profiles of mean droplet velocity, conditioned on the droplet size, at x/D = 20.

It appears that evaporation in this flow may be as much augmented by the mean slip as by the turbulence. As a numerical estimate of the relative importance of the mean slip velocity, $U_s = U_d - U_g$, we calculate the ratio U_s/u', where u' is the RMS turbulence velocity for droplets < 3 μm (not shown here). Throughout, u' has the expected behaviour in a simple shear flow: a local minimum on the axis and peaks in the middle of the shear layer, where the turbulence intensity, $u'/(U_g - U_{co\text{-}flow})$, peaks at a rather high value of 0.4. For large droplets (d > 30 μm), U_s/u' rises to 1.8 on the axis; in the shear layer values are lower, peaking at around 0.8. Thus, mean slip and turbulence can be expected to contribute roughly equally to evaporation in this size range.

To estimate the convective contribution to evaporation, a calculation of the Nusselt Number ($Nu \equiv 2 + 0.6\ Re^{0.5}\ Pr^{1/3}$), indicates that the Reynolds number dependent term makes an 80 percent addition to the still-air evaporation rate for a 30 μm droplet and 5 m/s slip velocity. This would be typical in the range of x/D = 10 to 25. The RMS turbulence velocity may make a further contribution of similar magnitude in this spray. This should provide fertile ground for testing evaporation- and convective models in numerical predictions.

Concluding Remarks

The above results demonstrate that quite accurate flux data can be obtained by phase-Doppler measurements when conditions are chosen to realize the full potential of the instrument. The simplicity of the geometry and boundary conditions in this study should enable CFD specialists to apply the results with confidence in almost any numerical scheme. The choice of a highly volatile liquid makes the data especially useful in testing evaporation models.

In the flames that we have probed with the PDA system on this burner (acetone and methanol), the sprays are denser than in the current cold jet sprays. We therefore expect that droplet fluxes would have been adequately recorded only some distance away from the nozzle.

It may prove feasible to use the LIF data collected, without stripping the droplet part, to obtain from these images alone a full measure of total acetone number density, and hence total flux. This would assume that the acetone molecule fluoresces equally in the liquid and vapour phase, a good approximation in fine sprays [2], and that droplet optics, quenching and other effects are not large. It would be a substantial advantage to be able to use this simple LIF technique routinely to collect space-resolved information on both vapour and liquid simultaneously. The present images, together with the PDA droplet data for verification, are now being processed to exploit this topic, also with a view to deriving a quantitative measure of droplet size distribution from the imaging data.

Acknowledgments

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