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].)

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.

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 intensified 12-bit CCD camera is used to maximize resolution and dynamic range.

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

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 the 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 pressure for fine and coarse droplets.

<table>
<thead>
<tr>
<th>CASE</th>
<th>LFS</th>
<th>HFS</th>
<th>HFD</th>
<th>HCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Reynolds number</td>
<td>15,300</td>
<td>30,000</td>
<td>30,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Liquid inj. rate, g/min</td>
<td>7.03</td>
<td>7.03</td>
<td>11.7</td>
<td>7.03</td>
</tr>
<tr>
<td>$D_{30}$ at nozzle exit, $\mu$m</td>
<td>9.3</td>
<td>12.0</td>
<td>13.4</td>
<td>17.1</td>
</tr>
</tbody>
</table>

Table 1. Experimental conditions.
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.

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 \( d < 3 \mu m \) size range are assumed to approximate to \( U_g \). It can also be seen that \( U_d \) in the range 10 - 30 \( \mu m \) closely approximates to the \( d < 90 \mu m \) range, i.e., all droplets.

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 \( d < 3 \mu m \) 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 \( \mu m \) may already have substantial slip velocities with the surrounding gas as is discussed below.

To estimate the convective contribution to evaporation, a calculation of the Nusselt Number \( (Nu = 2 + 0.6 Re^{0.8} Pr^{0.5}) \), indicates that the Reynolds number dependent term makes an 80 percent addition to the still-air evaporation rate for a 30 \( \mu m \) 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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### References


