Experimental characterization of isothermal and evaporative sprays

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Abstract

Introduction

In liquid-fuelled combustion, it is very important to gain fundamental understanding of phenomena such as interaction between the dispersed and continuous phases, droplet cluster formation [1] and group combustion [2] which largely govern the formation and combustion of air-fuel mixture. However, spray combustion involves different interacting processes such as chemistry, heat transfer, turbulent two-phase flow dynamics and evaporation and mixing, and thus its study is so complex that it is impractical to investigate all of the involved physical processes at once. Hence, there is a need to prescribe or even predict the spatial and temporal variations in the spray characteristics of a basic steady spray under isothermal and evaporative conditions, which is the aim of the present research.

There are two main aims in this paper. The first aim is to report the two-phase statistics, and specifically the measurement of droplet-gas spatial velocity correlations in an isothermal spray. The quantification of the velocity correlations (which are rare in literature - in particular in sprays with polydispersed droplets) is essential for the characterization of the momentum exchange between liquid and gas phases, in order to gain insight in the interaction between the two phases. A new approach of simultaneous planar measurement of droplet velocity and size with gas phase velocities is adapted for this purpose, based on a combination of the out-of-focus imaging technique 'Interferometric Laser Imaging Droplet Sizing' (ILIDS) [3] for planar simultaneous droplet size and velocity measurements with the in-focus technique 'Particle Image Velocimetry' (PIV) for fine tracer particle velocity measurements in the vicinity of individual droplets. An unexpected difficulty with the combined technique was the presence of a spatial discrepancy in droplet centre when calculated independently through ILIDS and PIV images, which would lead to erroneous velocity correlations between droplets and gas phase. The cause of this discrepancy, its quantification and a method for its elimination were addressed in [4, 5]. The ability of the technique to measure two phase statistics has been reported in [6].

The second aim is to describe the optical arrangement and data processing and demonstrate the combined ILIDS with fuel vapour 'Laser Induced Fluorescence' (LIF) measurements, which can provide simultaneous and planar measurements of vapor concentration and droplet size, velocity and concentration in an evaporative spray. This will measure the spatial correlation of vapor concentration around droplets with the droplet properties, like drop size, velocity and concentration, and can elucidate on the conditions under which group evaporation occurs and quantify the range of associated group evaporation numbers in an evaporative spray.

Experimental and Optical Arrangement

An overview of the experimental rig, for the isothermal spray measurements, is shown in Figure 1a. The present work employed a spray dryer rig for two phase measurements. The rig allowed coflowing air to enter from the top in the annulus around the atomizer, which was a custom–built air–assisted nozzle placed on the centerline of the cylindrical chamber with diameter of 0.5m. It produced a solid cone spray with a characteristic droplet diameter (SMD) of the order of 150–200μm at liquid feed rates of the order of 1.4-1.6×10-3 kg/s and air feed rate of the order of 0.12×10-3 kg/s. The coflowing air was seeded with aluminium oxide particles (diameter range 1-5 micron) before entering the rig. The coflowing air flowrate, carrying the seeding particles, was 200 lt/min, resulting in area-averaged air velocity 1.7×10-2m/s around the spray. A frequency-doubled, double pulse Nd:YAG laser (120 mJ/pulse at 532 nm; New Wave Research) was used to illuminate the flow. Two identical cameras were used (PCO; Sensicam QE, 12bit, 1040×1376) and positioned on the same side of the laser sheet. Two identical lenses (Nikon; 135mm focal length) were used to collect the scattered light from droplets. The scattered light from droplets was divided into two parts by using a beam splitter.

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The experimental set up for the evaporative spray measurements is schematically shown in Figure 2. This approach incorporates simultaneous illumination of the spray by two coincident laser sheets (wavelengths 532nm and 266nm). Acetone is chosen as a fluorescent marker with the 266nm as the excitation wavelength, because of the weak dependency of the fluorescent intensity on temperature. The peak in the optical spectrum of the fluorescent intensity occurs at a wavelength of around 435nm. The scattered light from the droplets is divided in two parts by a beam splitter; one part is directed to the ILIDS camera and the second part to the PLIF camera. For ILIDS, a cross–correlation camera is used under the defocused settings with appropriate lenses and a high pass optical filter (Filter 1) for collecting only the scattered light from the droplets. The intensified camera for PLIF can capture either the scattered light (to locate the droplet centre and quantify centre discrepancy, as explained later) with a low pass optical filter (Filter 3) or the fluorescent intensity by using a band pass optical filter (Filter 2).

Results and Discussion

For the isothermal, non evaporating spray, the statistical properties of the dispersed phase (for three droplet size classes) and continuous phases are obtained at five different cross-stream locations, 500 mm downstream and at a 125 mm off-axis location in the spray, as shown in Figure 1b. Stokes number of the droplets based on time scale of large scale structures in the flow is much less than unity and, lies in the range of 0.01 to 0.05. An example of these measurements for the innermost measurement location of the spray is presented in Figure 3, which shows the area-averaged droplet-gas spatial velocity correlations, *conditional* on droplet size, and the droplet-droplet velocity (same size class) and gas velocity spatial correlations for both *axial* and *cross-stream* components of velocity (denoted by u and v respectively)., It can be observed the similar order of magnitude of the correlations for both *axial* and *cross-stream* components of velocities, signifying the presence of one-way coupled flow between the dispersed and continuous phase. In order to identify the large scale structures present (if any) in the continuous phase, Proper Orthogonal Decomposition (POD) is applied over the gas phase velocity field. Contributions of individual POD modes (eddy structures) on the droplet-gas velocity correlation are obtained by reconstructing the instantaneous fluid phase velocity by considering the particular mode and recalculating the correlations. Figure 4 presents the modal contributions of the structural eddies (present in the continuous phase) towards the droplet-gas correlation for the *axial* direction. The 1st mode is the dominant contributor to the correlations in the *axial* direction, while (not shown here), the 2nd mode is dominant in *cross-stream* direction.

As discussed before, for the evaporative spray, simultaneous measurements of vapour concentration around individual droplets along with the droplet properties are accomplished by combining ILIDS with LIF., However, the combination of out–of–focus and in focus techniques results in a discrepancy in the location of the droplet centre [4, 5], which has been addressed for the combined ILIDS and PIV system. This issue will remain for the combined ILIDS (out-of-focus) and PLIF (in-focus) measurements and will lead to erroneous correlation between droplet size/velocity (from ILIDS) and vapor concentration obtained from LIF. In order to avoid such error, the same approach of [4, 5] is followed and the droplet centre discrepancy is quantified by capturing the scattered light simultaneously both at the ILIDS and LIF cameras with adequate optical filters. Then, the droplet centre position, calculated from the defocused fringe patterns of the ILIDS technique, is corrected so that, at a later stage, the measured droplet properties can be correlated correctly with vapor concentration.

Final paper

The final paper will present mean droplet and gas phase velocities at various measurement locations. The area averaged droplet-gas spatial velocity correlations, *conditional* on droplet size, will be presented and compared with the droplet-droplet velocity (same size class) and gas velocity spatial correlations for both *axial* and *cross-stream* components of velocity. The final paper will include the above results along with the selective influence of POD modes over droplet-gas velocity correlations for different size classes and for various cross-stream locations and, comparison among them.

It will then proceed to describe the combined ILIDS-PLIF technique (the optical arrangement, experimental procedure and image processing algorithms) together with a discussion of associated uncertainties and limitations. The approach will then be demonstrated in a stream of mono-sized acetone droplets, produced by a custom-made droplet generator, before proceeding to a polydisperse spray. The measurements in the monodisperse droplet stream will evaluate the uncertainties and limitations of the technique before applying it to a polydisperse spray. In addition, the study of the behaviour of the vapour envelope around the monodisperse droplet stream as a function of droplet size and inter droplet distance will provide insights into the physics of evaporation of droplet clusters. The method will then be demonstrated in a polydispersed spray and spatial correlations between the vapour concentration distribution and droplet size and velocity will be presented.

References

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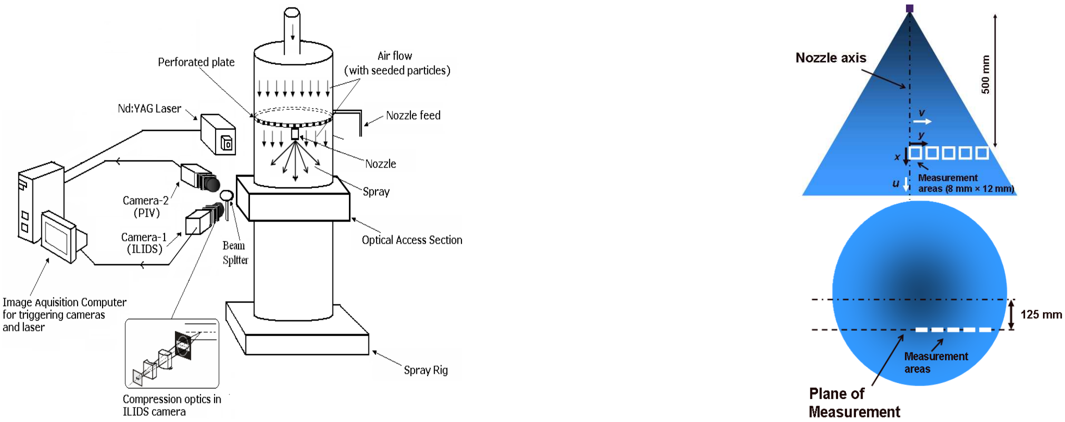

Figure 1: (a) Experimental set-up for the combined ILIDS and PIV measurements, (b) Elevation view (top) and Plan view (bottom) of the measurement locations in the spray

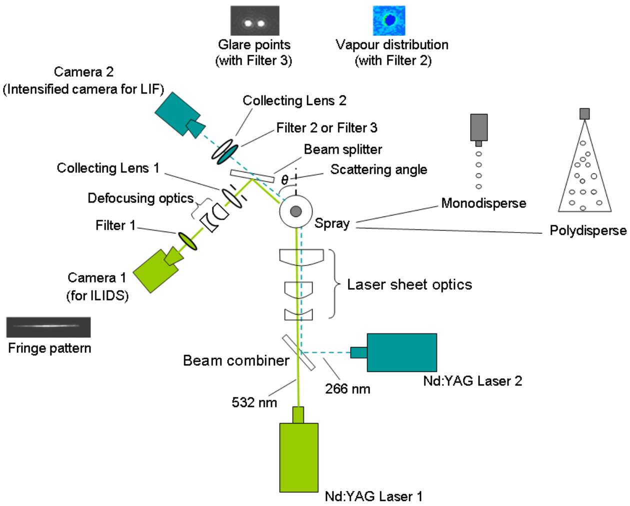

Figure 2: Schematic of the experimental set-up for the combined ILIDS and PLIF techniques.

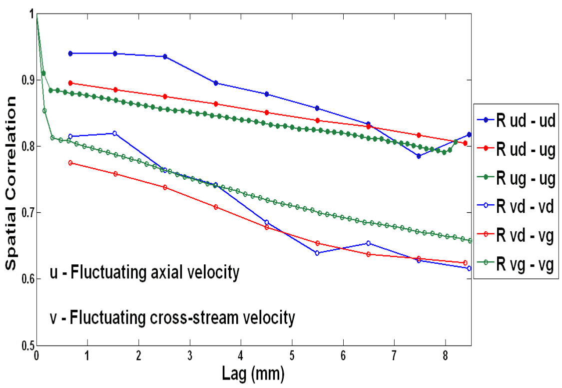

Figure 3: droplet-droplet, droplet-gas and gas spatial velocity correlation for droplet size class of 20-35 µm.

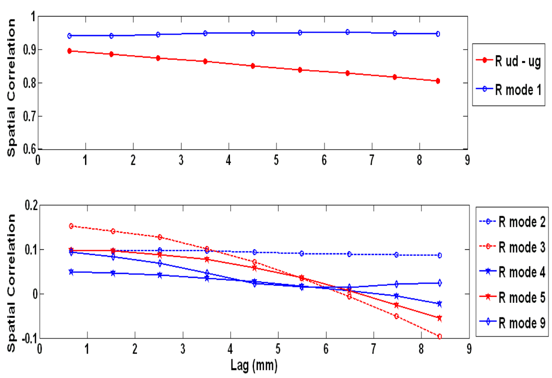

Figure 4: Modal contributions to droplet-gas *axial* velocity correlation for droplet size class of 20-35 µm.