PDA measurements of droplet size and mass flux in the three-dimensional atomisation region of water jet in air cross-flow

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Abstract The main objective of this paper is to develop a technique to measure the global droplet properties in the atomisation region of a water jet issuing in a high-speed air cross-flow. Knowledge of these global properties allows comparison of the break-up outcome of geometrically different water nozzles. This is achieved by extending a PDA system to enable measurements in three-dimensional droplet flows.

First, the droplet size and the spatial droplet distribution are measured by the PDA method. The global droplet properties are then obtained by using the measured local mass flux as a weighting factor in integrating the local droplet size. To facilitate the measurement of mass flux in three-dimensional flows, the PDA method is extended so that the reference area for the mass flux is derived as a function of both the geometry of the measurement volume and the flow direction. In the present application of three-dimensional droplet flow (a water jet in air cross-flow), a simple method is developed to measure the three velocity components of droplets by means of a two-component PDA system. The paper outlines the measurement technique and the procedure of estimating the global droplet size and the global droplet size spectra from local droplet properties and local mass flux.

1 Introduction

In many two-phase flow applications, such as water injection in superheated steam cross-flow or fuel injection in air cross-flow, the thermal efficiency of the process is strongly dependent on the evaporation time of the injected liquid. This evaporation time, in turn, depends on the break-up mechanism of the liquid jet and the resulting droplet properties. In order to be able to evaluate the break-up outcomes satisfactorily, it is necessary to know the spatial distribution of the droplet flow as well as the local and global spectra of droplet size. Such characteristics cannot be obtained, with reasonable accuracy, by numerical means because of the complexity of the break-up mechanism of liquid jets in cross-flow. Experimental techniques are often used to obtain reliable estimates of droplet properties (Faeth et al. 1995; Zhang et al. 1998). The results may then be used as input to computational fluid dynamic codes to simulate the trajectories and evaporation time of these droplets.

One of the most valuable methods to measure the properties of droplets, or of particles in general, is the Phase Doppler Anemometry (PDA). This method enables measurements of both the particle velocity and size. However, since each individual measurement provides information about a single point in the flow, the estimation of global averaged particle properties in a flow field with non-uniform particle distribution is not a straightforward matter. The local particle size distribution must be integrated spatially by means of a weighting factor proportional to the local mass flux. As a vector quantity in the flow, the mass flux is directed in the flow direction. The most important step in measuring the mass flux by means of PDA method is the determination of the cross-sectional area in the measurement volume. This area, as the reference area for the mass flux, depends not only on the particle size but also on the flow direction of the particles. The former dependence is usually simulated, although not ideal, by the burst length method according to Saffman (1987), whereas the latter dependence is obvious, because only the absolute particle velocity (not a velocity component) and the cross-sectional area of the measurement volume normal to the particle flow direction determine the oncoming rate of particles and thus the mass flux. The necessity to know the flow direction of particles and the cross-sectional area of the measurement volume normal to the particle flow direction constitutes the main difficulty which greatly limits the application of PDA systems in practical three-dimensional flows. First, most PDA systems are two-dimensional and do not enable measurement of the third velocity component. Secondly, an explicit expression of the cross-sectional area of the measurement volume normal to the flow direction does not exist. Even in the case of two-dimensional application of PDA systems, the assumption of a linear dependence of the cross-sectional area of the measurement volume on the flow angle has to be made (Dantec PDA-Manual 1997). Accordingly, PDA systems are usually set up with their optical axis perpendicular to the flow direction, and the flow is then considered to be locally two-dimensional. The application of PDA systems in three-dimensional flow cases is therefore hampered, because the flow direction changes with location.

It should be mentioned that in measuring the mass flux of droplets by means of the PDA method, selecting the relevant
reference area can be a source of error. The mass flow through a flow area $A$ may be calculated from the mass flux $\dot{m}$ as $A(n \cdot \dot{m})$ with $n$ as the unit vector normal to the area $A$. Conversely, the mass flux as a vector quantity may be obtained from the mass flow if the projection of the flow area $A$ on a plane normal to the flow direction is taken to be the reference area. The projection area therefore plays a key role in calculating the mass flux from the mass flow measurement. Because in PDA measurements, the summation of all the particles per unit time represents just the particle mass flow through the measurement volume, the mass flux may be obtained if the projection of the measurement volume in the direction of the particle velocity (and not in the direction of a velocity component) is taken as the reference area. In the present paper firstly, the procedure used to measure the mass flux is described briefly. Thereafter, an expression of the cross-sectional area of the measurement volume normal to the particle flow direction is derived. The developed procedure is then used to measure the break-up outcome of a water jet issuing in air cross-flow. Since the droplet flow is three-dimensional, a simple procedure for its measurement by means of a two-component PDA system is worked out. The measured local mass flux is then utilised as a weighting factor to estimate the global averaged droplet properties. These global properties have been found to be very useful when comparing the atomisation efficiency of geometrically different water nozzles.

2 Mass flux and its measurement

Mass flux measurement with the aid of the PDA method is based on the temporal sampling of particles passing through the measurement volume. This sampling process involves a direct coupling between the PDA signal and the mass flux vector ($\dot{m}$) directed in the particle flow direction. To demonstrate this character of the mass flux measurement, a constant flow ($c$) with homogeneous monodisperse particles distribution ($n = \text{const.}$ in number/m$^3$) will be assumed. Furthermore the measurement volume is assumed to have a cross-sectional area $A$ normal to the flow direction. The mass flow of particles passing through the measurement volume is then calculated by

$$M = \frac{1}{\rho} \pi d^3 n c A$$

(1)

The product $n c A$ in the equation represents the oncoming rate of the particles, i.e. the data rate (DR) in PDA measurements. Since the data rate is indeed one type of PDA signals, it may be concluded that the quantity

$$\dot{n} = \frac{M}{A} = \frac{1}{\rho} \pi d^3 \frac{\text{DR}}{A}$$

(2)

is coupled directly with the PDA measurement. It is the absolute value of the mass flux vector directed in the flow direction ($|\dot{m}| = \frac{1}{\rho} \pi d^3 n c$). This feature of the mass flux measurement is unique to this method in comparison to the velocity measurements where the components of velocity are always measured.

The component of the mass flux, for instance in the $x$-direction deviated from the mass flux vector by $\alpha$, is then given by

$$\dot{m}_x = \dot{m} \cos \alpha = \cos \alpha \frac{\rho \pi}{6A} \sum d^3$$

(3)

As can be seen, this component of mass flux is related to the absolute value of the mass flux vector and is independent of the cross-sectional area of the measurement volume normal to the $x$-direction. It should be mentioned here that in some previous studies the flow areas corresponding to individual directions ($A_x, A_y, A_z$) are used to calculate the corresponding mass flux components. This approach is likely to lead to an error in calculating the mass flux, especially if the measurement volume differs largely from a spherical form (constant flow area in all directions).

In practical flows with non-monodisperse particles and with fluctuating flow velocity (both in absolute value and in direction) the average of the mass flux is normally expressed by its components. Both the particle size and the flow direction of particles need to be classified. For this purpose Eq. (3) is generally modified to

$$\dot{m}_x = \sum \dot{m}_k \cos \alpha_k = \frac{\rho \pi}{6A} \sum \cos \alpha_k \sum \frac{d^3}{A(d_k, \alpha_k)}$$

(4)

where the index $k$ indicates the classification of the particle flow direction. The classification of the particle size is also suggested, because the cross-sectional area of the measurement volume depends additionally on the particle size. The mass flux measurements according to Eq. (4) is only accurate if all the particles passing through the measurement volume are sampled and the number of samples is sufficiently large for statistical accuracy. Usually there are always samples which are rejected owing to the spherical validation, Gaussian effects and other uncertainties. Most PDA systems use this rejection rate to correct the mass flux measurement. For particles having a broad spectrum distribution, a large number of samples is necessary in order to ensure statistical accuracy for large particles (which have a very strong effect on the mass flux measurements).

In stationary flows with moderate turbulence level (e.g. <50%), the local flow direction of particles can be approximated to be the same for all classes of droplets ($\alpha = \text{const.}$). The variations in flow direction due to the flow turbulence may also be considered to have negligible influence on the measurement. The value of the mass flux is then

$$\dot{m}_x = \cos \alpha \cdot \dot{m} = \cos \alpha \frac{\rho \pi}{6At} \sum \frac{d^3}{A(d_i)}$$

(5)

The absolute mass flux $\dot{m}$ here is calculated by the scalar sum of the mass fluxes given by the ensemble of the particles.

From Eqs. (2) to Eq. (5) it is evident that, to calculate the mass flux, the cross-sectional area of the measurement volume normal to the flow direction has to be known. While the dependence of the cross-sectional area of the measurement volume on the particle size is usually described by the burst length model (Saffman 1987) or, in few applications, by the burst integration model (Sommerfeld and Qui 1995), details about the derivation of the cross-sectional area of the measurement volume in relation to the flow direction are given in the following sections.