The time-shift technique for measurement size of non-transparent spherical particles

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INTRODUCTION

In this study we introduce the time-shift technique, also known as the pulsed-displacement technique, as a means of measuring size and velocity of spherical particles. The measurement technique is not new, it has been introduced by Semidetnov[1] in 1985 and more generally discussed by Hess and Wood[2], Lin et al[3], Damaschke et al.[4] and Albrecht et al[5]. The novelty introduced in this study is the application of the technique to measure non-transparent particles, which are quite common for example in spray drying processes or in paint sprays. In this contribution the basic working principle of the time-shift technique will be reviewed and an optical configuration suitable for the measurement of non-transparent droplets will be presented. The signal generation and processing will be discussed. Example measurements in a milk spray are presented.

METHODS

The measurement principle of the time-shift technique is only briefly summarized here, since adequate descriptions can be found elsewhere. e.g. Albrecht et al. 2003[5]. The measurement principle of the time-shift technique is based on the light scattering of a single particle from a shaped light beam, whereby the size of illuminating beam must be of the same order in size or smaller than the particles to be measured. The light scattered from a single particle can be interpreted as the sum of all scattering orders present at the detector location. With the geometrical optics approximation this corresponds to examining the propagation of individual rays of light through the particle with varying number of internal reflections, as described in detail by van de Hulst[6].

The typical experimental setup consists of one light source and two photodetectors placed around the light source (see Figure1a). The light is focused by an optical system to a light beam with a small beam waist. The measurement volume is defined by the size of illuminating beam and the imaging optics in front of the detectors. An example signal of a single milk particle passing through the measurement volume is shown in Fig. 1b.

In the case of non-transparent particles, e.g. droplets of emulsions, dispersions or suspensions, refracted light rays will no longer propagate undisturbed through the droplet due to absorption or secondary scattering from the dispersed phase, and these rays no longer contribute directly to the scattered light at a given detector position. Nevertheless, light entering such particles can scatter from scattering centers of the dispersed phase within the particle and this may result in some scattered light intensity observed at the detector (Figure 1a). The analog signal arising from this portion of scattered light will be termed the baseline signal, or signal pedestal.

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This analog signal obtained from such non-transparent droplets exhibits two main features: the first is the signal pedestal arising from the internal scattering in the particle and extending over a residence time *d/v*, i.e. the particle diameter divided by the velocity of the particle normal to the illuminating beam. The second feature is the reflective peak, appearing at different times for each detector, the exact time being dependent on the respective detection angle, the particle velocity and the droplet diameter. Knowing the geometric parameters of the optical configuration, the time shift between the two reflective peaks is linearly related to the particle diameter, if the droplet velocity is known.

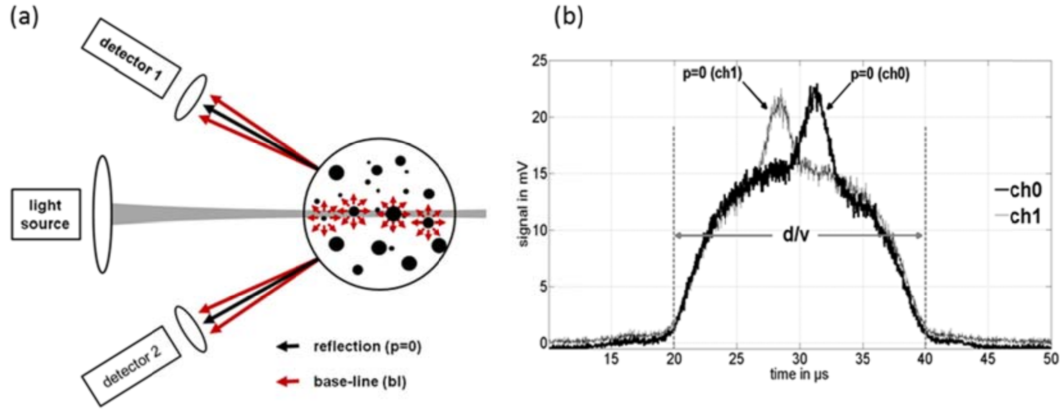

Figure 1 a) Schematic representation of the optical configuration; b) Time-shift signals obtained from a two-detector time-shift measurement system obtained for a milk droplet passing through the measurement volume.

An empirical expression describing the signal can be given as:

$$S(t) = \underbrace{C_0 w_0 \left(d^2 - 4v^2 (t-t_0)^2\right)}_{baseline} + \underbrace{\sum \frac{A_p}{C_p} \exp\left\{-\frac{2\left((t-t_0) \pm t_p\right)^2}{\sigma^2}\right\}}_{refraction} - \underbrace{A_0 \exp\left\{-\frac{2\left((t-t_0) \mp t_{p=0}\right)^2}{\sigma^2}\right\}}_{reflection} \quad [1]$$

comprising three terms. The first term corresponds to the pedestal, whose amplitude will be related to the scattering center concentration in the droplet C_0. For a completely non-transparent particle (like metal particles) the pedestal will not appear. This component has been approximated by a width of (*d/v*), where *d* is the particle diameter and *v* the particle velocity component parallel to the scattering plane defined by the illuminating beam and the two detectors. The second term describes the higher-order refractive components, but will be neglected for all but the most dilute particles (non-transparency). This term is Gaussian in shape, corresponding to the shape of the illuminating beam, which will be assumed to be a focused laser beam. The last term corresponds to the reflective scattering and is also represented by a Gaussian curve of width σ, whereby σ will be linearly proportional to the illuminating beam waist and inversely proportional to the particle velocity. Using this signal model, the time-shift technique has been used for measuring the size of milk particles in a spray. A pre-requisite to compute the droplet size is to know the particle velocity, which for the present measurements has been obtained using a time-of-flight technique.
For the time-of-flight measurement two parallel light beams with a space Δb between them are used such that each detector sees both beams (Fig. 2a); hence, each detector registers two signals from each particle. The time separation between these two reflection peaks is given by

$$\Delta t_{TOF} = \frac{\Delta b}{v} \quad [2]$$

from which the particle velocity can be calculated, knowing Δb and measuring the time separation Δt_{TOF} .

The reflection peaks in the signals on detectors 1 and 2 also have a time separation, which is known as a time-shift and is given by

$$\Delta t_{TS} = \frac{d/2}{v}\left[\cos\left(\frac{\theta_S^{(1)}}{2}\right)+\cos\left(\frac{\theta_S^{(2)}}{2}\right)\right] \quad [3]$$

where $\theta_S^{(1)}$ and $\theta_S^{(2)}$ are the known scattering angles for the two detectors.

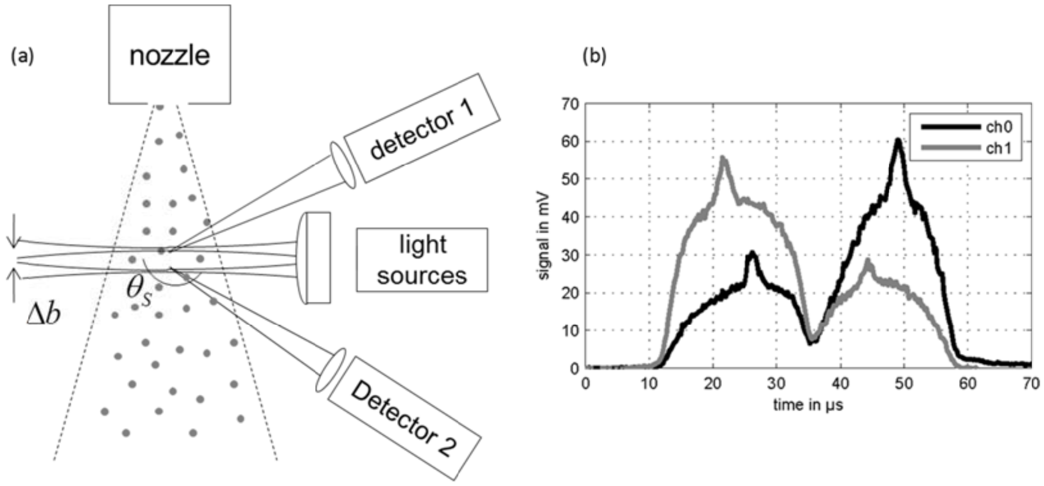

Figure 2 a) Schematic illustration of the experimental setup with time-of-flight optics. *Δb* is the distance between two parallel light beams and θ_S indicates the scattering angle; b)Typical time-shift signals originating from a single milk particle passed through the two measurement volumes. ch0 indicates the signal originated from detector1 and ch1 from detector2.

EXPERIMENTAL RESULTS

In the experimental setup (Figure 2a) two light sources, whose beams are focused to a light sheets using a single cylindrical lens, are used to create two parallel focused light sheets. The displacement between two focused light sheets can be varied mechanically and measured using a beam scan device. The thickness of the first beam sheet is 26.64µm and of the second 27.02µm; the displacement between them is 247.2µm. Two photomultipliers are placed symmetric about the two light beams: the scattering angle for detector 1 is 147deg for detector 2 160deg.

For demonstration a milk spray with a fat content of 3.5% was used. The milk spray was created by flat fan nozzle (Lechler [27], Type: 632.363) operated at 2bar, 3bar and 4bar pressure. The downstream distance from the nozzle to the measurement position was 150mm. A signal originating from a single milk particle passing through two light beams is shown in Figure 2b. Two peaks of reflection and two pedestal signals can be recognized. The high concentration of fat particles inside the milk suppresses higher order refractive scattering.

Four steps are required for calculating particle velocity and the particle size from the time-shift signal (Figure 2b): signal acquisition, signal detection, peak detection and calculation of time separations. The signal acquisition must be fast enough to resolve the peaks in the time-shift signals. The signal detection is required to select signals portions containing useful information. If this is done using amplitude threshold, a level too high will recognize only signals from larger particles; a level too low will mistake noise for signal. After the time-shift signals are acquired and detected, the peak detection takes place. The primary task of the peak detection step is to find the time position of peak maxima with minimal error. There is a multitude of algorithms for determination of the peak position. For example, the peak detection can be done by fitting a

parabola to the three points with maximum amplitude. Once the peak positions are determined, the particle size and velocity can be calculated using Eqns. (2) and (3).
The experimental results are illustrated in Figures 3 and 4. The particle size distributions for different nozzle pressures are shown in Figure 3a. At high nozzle pressure the milk spray includes smaller particles. Increasing the atomization pressure also leads to an increase of the mean particle velocity (Figure 3b).

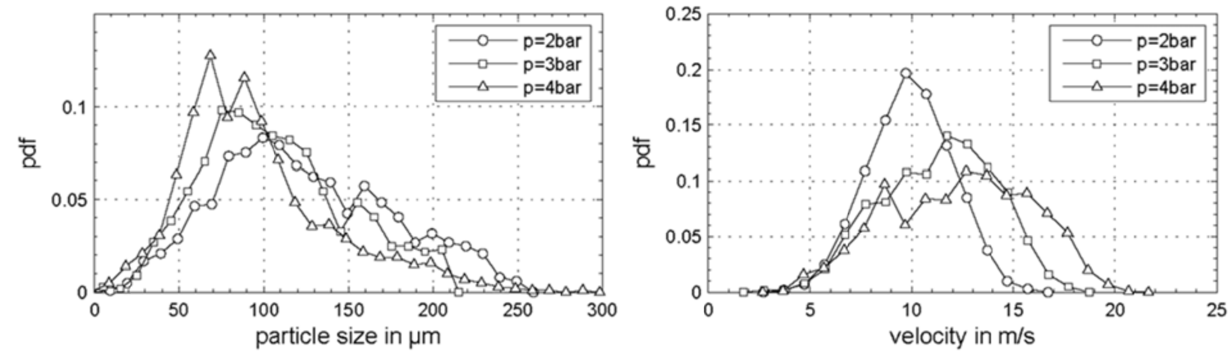

Figure 3: Probability density function of a) Particle size and b) particle velocity from a milk spray measured using the time-shift technique

The correlation between the particle size and velocity is depicted in Figure 4, from which it is evident, that larger particles have higher velocities. This weak correlation is consistent with expectations of particles being injected into quiescent air. No other measurement method presently offers the possibility of obtaining similar results in a milk spray, therefore, the absolute accuracy of these measurements cannot be directly verified by comparison to another instrument; nevertheless, the main dependencies demonstrated at different pressures follow expectations.

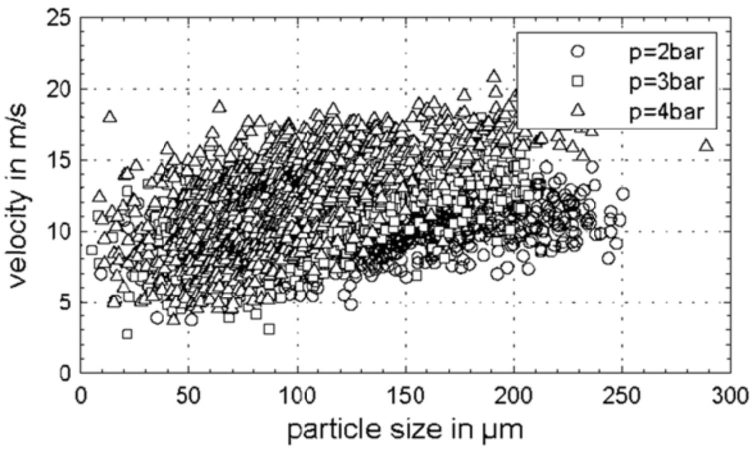

Figure 4: Correlation between particle velocity and particle size.

CONCLUSION

The primary aim of the present work was the further development of the time-shift technique for characterization of dispersion/emulsion droplets in a spray. Although this measurement technique has been known for over 20 years, until now it has not been applied to spray characterization because of several secondary problems which have been outlined and partially solved in this study. The study concludes with example measurements, demonstrating the functionality of the measurement technique. The example measurement was performed with a combination of time-shift technique and time-of-flight technique to measure the size and the velocity of the droplets respectively.

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