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Validation of the Time-Shift Technique for Spray Characterization

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Abstract

The present study focuses on a comparison between the phase Doppler technique and the time-shift technique. This comparison is made using a water spray generated by a full cone nozzle. Drop size distributions, drop velocity distributions as well as correlations between size and velocity are analyzed at given positions in the spray. Despite minor differences, good overall agreement between results obtained by the phase Doppler technique and the time-shift technique is found. Additionally, the reasons leading to differences between the techniques have been identified and discussed. Finally, the potential of the time-shift technique is demonstrated by the characterization of sprays generated from non-transparent liquids.

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Introduction

Spray characteristics play an important role in a wide range of industrial applications, such as spray coating, spray drying and pesticide deposition. Spray characterization methods are thus essential tools for quality assurance, development and optimization of these processes; a review of measurement methods and corresponding techniques for spray characterization is available in Tropea (2011) [1]. Currently, the phase Doppler technique is state-of-the-art for spray characterization, i.e. the measurement of drop sizes and drop velocities; a good review about this technique is given in [2], [3] and [4]. However, robust operation of the phase Doppler technique is ensured only for transparent liquids. This drawback has recently been overcome by the time-shift technique [4], [5], [6] and [7] that can be employed for transparent, semi-transparent and non-transparent liquids.

The time-shift technique is a known measurement technique which was first introduced by Semidetnov (1985) [8] and was further developed by Damaschke et al. (2002) [4] und [5]. The time-shift technique has also been called the pulse displacement technique and several variations have been discussed by Hess and Wood (1994) [9] and Lin et al. (2000) [10]. Although the time-shift technique has been discussed in many studies and some simple validation, for instance, using glass beads and droplet generators has been introduced in [6] and [11], a rigorous comparison between the phase Doppler and time-shift techniques is essential to confirm the time-shift technique as a measurement method for a particle/droplet characterization in a spray.

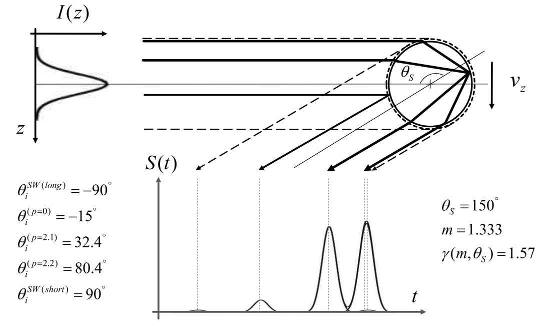

Figure 1. Basic principle of time-shift technique.

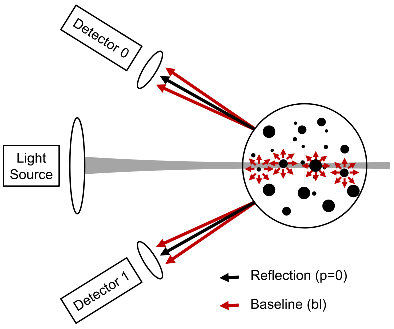

Figure 2. Schematic representation of the optical configuration [7].

Basic Principle of the Time-Shift Technique

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) [4]. The measurement principle of the time-shift technique is based on light scattering of a single particle from a shaped light beam. Whether the intensity variation is Gaussian, as would be the case for a laser beam in TEM00 mode, or any other form, is not important, in principle. However some advantages can be recognized for the subsequent signal processing if a Gaussian beam is used.

The light scattered from a single spherical particle can be interpreted as the sum of all scattering orders present at the detector location. The intensity of the scattering orders are described by the Debye series [12] expansion of the Mie [13] scattering functions, or by using a geometric optics approach [14], [15] to compute the scattered field. When a particle/droplet passes through the focused light beam, the scattered light is detected by photodetectors focused onto the scattering center. Each photodetector provides a time signal known as a time-shift signal (see in **Figure 1**). Depending on the scattering angle and relative refractive index, different scattering orders and their modes can appear [6], consequently through placement of the detector certain scattering orders can be selected. The signals from upper and lower detectors have mirrored signals in time.

An example time-shift signal originating from a water droplet passing through a Gaussian shaped beam and collected at a scattering angle of 150deg from backscatter is illustrated in **Figure 1**, in which signal components are observable from the following scattering orders: surface wave long path, reflec-

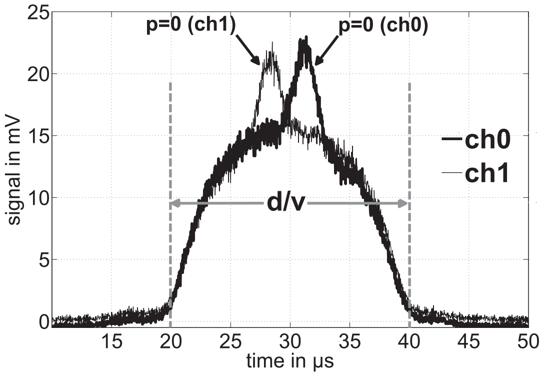

Figure 3. Time-shift signals obtained from a two-detector time-shift measurement system (see **Figure 2**) obtained for a milk droplet passing through the measurement volume [7].

tion (p=0), second-order refraction mode 1 (p =2.1), second-order refraction mode 2 (p=2.2) and surface wave short path. The time between individual peaks in the time-shift signal will depend on the detection angle, the relative refractive index, the particle velocity normal to the illuminating beam, and the particle size. If the first two parameters are known and the particle velocity is measured, e.g. using a laser Doppler or time-of-flight technique, then the particle size can be deduced from the time shift between two of the signal peaks [6].

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. Consequently, the time-shift signal includes only a reflection peak and no further peaks corresponding to refraction. Nevertheless, light entering the suspension/emulsion 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 2**). The analog signal arising from this portion of scattered light will be termed the baseline signal, or signal pedestal. In the **Figure 3** the reflection peaks can be seen as well as the parabolic pedestal [7].

Experimental Setup

The goal of the present study is the comparison of the time-shift and phase Doppler techniques. Consequently, it must be first guaranteed that both measurement techniques measure at the same point and second, that they measure under the same conditions. For that reason, the measurement volumes of both measurement setups have been be overlapped and, additionally, both systems have been operated simultaneously so the measurement of particle size and particle velocity has taken place simultaneously.

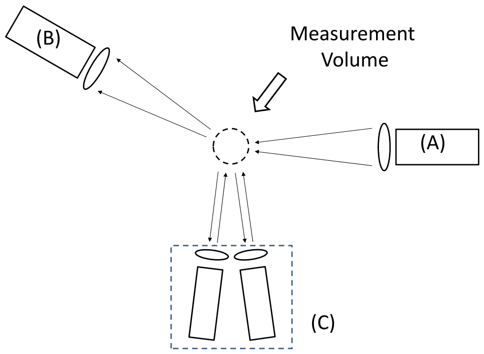

Figure 4. Schematic illustration of experimental setup.(A) and (B): phase Doppler setup. (C) Time-Shift setup.

The schematic illustration of the experimental setup is depicted in **Figure 4**. The phase Doppler setup (DualPDA von Dantec Dynamics with Stabilite 2017 Laser von Spectra Physics [16]) and the time-shift setup (SpraySpy SSA15VW125 [17]) has been placed on a single plane. The position of the measurement head of time-shift setup is perpendicular to the transmission optic of the phase Doppler. In the time-shift setup two wavelengths 405nm and 450nm have been used as illuminating beams and in the phase Doppler the wavelengths 488nm and 514nm have been used. Using suitable band pass filters in both setups it can be guaranteed that both measurement setups do not influence each other. Additionally, **Figure 5** pictures the experimental setup, where the overlapped beam from phase Doppler und time-shift setups can be seen.

Experimental Results

In this work two experimental results will be presented: the first measurement has performed done to validate the time-shift technique as a measurement method for particles/droplets characterization in a spray and the second measurement demonstrates the ability of the time-shift technique to measure the size and the velocity of non-transparent particles/droplets in a spray. In both

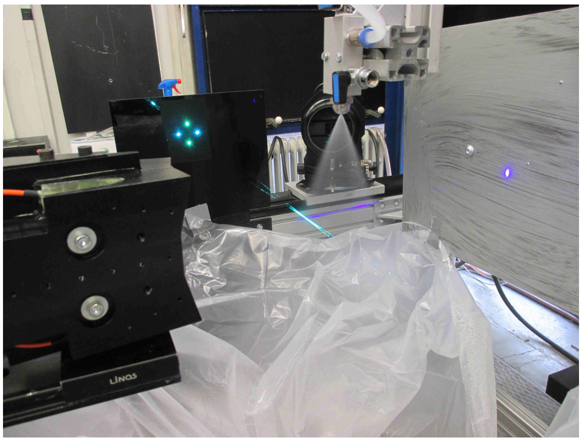

Figure 5. Photo of the experimental setup. (left) time-shift setup. (right upper corner) the receiving optic of phase Doppler.(top) the full cone nozzle.(middle) overlapped light beams.

measurements the spray was created by the full cone nozzle from Schlick 121 1.7 / 30 operated at 6 bar. In the first measurement water has been used and in the second milk with a fat content of 1.5%. The measurement volume is placed 8cm below the nozzle and the spraying is done in non-moving air. To guarantee reliable results, the phase Doppler system was setup up to reach a spherical validation over 90%.

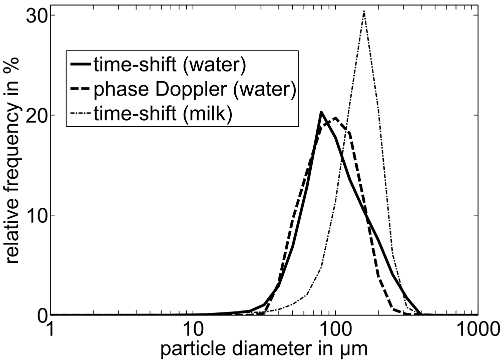

Figure 6. Particle size distribution measured by time-shift (solid line) and phase Doppler (dashed line) techniques. (thin dashed line) Particle size distribution of milk spray (1.5% fat content) measured by the time-shift technique.

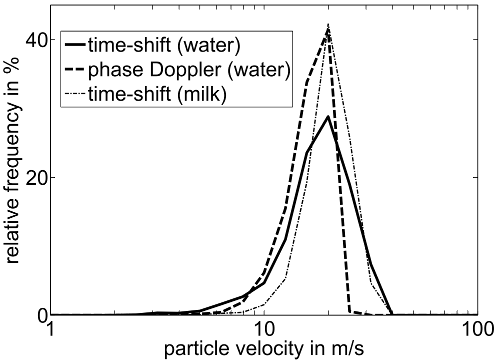

Figure 7. Particle velocity distribution measured by time-shift (solid line) and phase Doppler (dashed line) techniques. (thin dashed line) Particle velocity distribution of milk (1,5% fat content) measured by the time-shift technique.

The results of both measurements are depicted in **Figure 6** and **Figure 7** and the median values of distributions are listed in **Table 1**. The particle size distributions of water spray measured by phase Doppler and time-shift techniques are in good agreement. The median values differ by less than 2%. In contrast, the measured particle velocity distributions from the time-shift and phase Doppler techniques shown in **Figure 7** exhibit a deviation larger than 8% which is attributed to several effects. First, only one velocity component is compared, which may not be the same for both measurement volumes, since the spray is measured from different directions. Additionally inaccuracies regarding the measurement setup lead to slightly different results.

	median(d)	median(v)
Time-shift (water)	105.8 μm	19.1 m/s
Phase Doppler (water)	104.5 μm	20.8 m/s
Difference in %	1.2%	8.1%
Time-shift (milk)	169 μm	22.8 m/s
Difference in %	37.8%	12.5%

Table 1. Median values of measured distributions.

In the second experiment the size and velocity of non-transparent particles in a spray at the same condition is measured. For this measurement the milk with a fat content of 1.5% has been used. In **Figure 6** and **Figure 7** the measured size and velocity distribution are also depicted. The milk spray has a similar velocity distribution as that of water, whereas the particle size distribution exhibits a large deviation of 37% compared to the water spray, indicating that the milk results in larger droplets.

Conclusion

In this study the comparison between time-shift and phase Doppler techniques has been presented. In particular, a full cone nozzle from Schlick 121 $1.7/30^o$ operated at 6 bar was characterized at a fixed position. We proved that the time shift technique is valid to measure size and velocity of transparent particles in a spray process. The results of both techniques show good agreement when measuring the parameters. Additionally, small variations between the results of both techniques are analyzed and discussed. In the second part of this study the time shift technique was verified to characterize non transparent particles. The size and velocity from milk particles with a fat content of 1.5% was successfully measured at the same nozzle. We observed that the average drop size increases when spraying milk instead of water, while the velocity distribution stays approximately constant.

Acknowledgement

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Nomenclature

d	particle/droplet diameter
v	particle/droplet velocity
$ch0$	channel 0, signal from detector 0
$ch1$	channel 0, signal from detector 1

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