DETERMINATION OF DROPLET SIZE AND VELOCITY DISTRIBUTIONS IN A TWO-PHASE WIND TUNNEL

Thomas Hagemeyer*, Róbert Bordás*, Péter Renes**
Bernd Wunderlich*, Dominique Thévenin*
*Department of Fluid Dynamics and Thermodynamics
University of Magdeburg “Otto-von-Guericke”
**Department of Fluid and Heat Engineering
University of Miskolc

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Visualization method(s): Shadowgraphy, PDA, LDV
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ABSTRACT: For a quantitative characterization of sprays (droplet size and velocity distributions) several optical methods are available besides the Laser-Doppler techniques (LDV, Laser-Doppler Velocimetry for velocity; PDA, Phase-Doppler Anemometry for simultaneous measurement of particle size and velocity) such as e.g. Shadowgraphy. Applying these techniques it is not only possible to determine the particle diameter and the size distribution of the spray, but also some information on the particle shape using Shadowgraphy. The quality of these measurement results can be assessed by a cross-comparison between the three different methods (LDV, PDA, Shadowgraphy). One specificity of the present experiments is that they are carried out using a spray injected into a two-phase wind-tunnel, so that carefully controlled and reproducible properties can be chosen for the liquid as well as for the gas phase. Different spray heads can be employed, leading to a mean Sauter diameter varying typically between 20 and 700 microns. In this publication it will be shown how to apply properly both the PDA and the Shadowgraphy technique in order to get accurate results for velocity, drop size and shape. A further optical method, an improved LDV-system developed within our group, is also available and used to determine the velocity of both phases and to measure the diameter distribution of the disperse phase.

1 Introduction

Nowadays, multiphase flows are of central interest in nearly every part of scientific and industrial research projects. Among them, the controlled generation and experimental simulation of rain generation in a two-phase wind tunnel remains a very rare application. Different types of atomizer lead to very different droplet sizes. Twin fluid atomizers can generate droplets with mean diameters in the range of 50 μm, as needed to simulate rain generation [1]. Together with low wind tunnel velocities this is suitable to reproduce droplet size and velocity distributions in cumulus clouds during the first stage of rain formation. As an alternative, pressure atomizers can be used to produce droplets with mean diameters of several hundred microns, as needed to simulate rain droplets at ground level [2].

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these atomization modes can be realized and combined with a broad range of air velocities in our two-phase wind tunnel. Therefore, different research fields (meteorology, soil erosion, tillage, automotive…) can be covered, investigating the atomization process and the resulting two-phase flows of water spray and air using a single set-up.

2 Experimental Setup

The experimental investigations have been carried out in a two-phase wind tunnel with recirculation (Göttinger type). A closed circuit for the air flow inside the wind tunnel was combined with an additional system for the water supply, atomization and recycling, as can been seen in figure 1.

![Figure 1: Scheme of the air and water flows in the set-up](image)

During the experiments the test section of the wind tunnel was closed, as it is necessary for the two-phase working mode. Optical access to the wind tunnel was possible through optical windows, one on each side of the rectangular-shaped test section. The dimensions of the windows are a length of 450 mm and a height of 400 mm. The spray was generated by a pressure atomizer with internal spin generator. It was located within the wind tunnel, along its central axis, 620 mm before the front edge of the window. The considered spray was quite dilute, contains large droplets and is directed co-current to the air flow of the wind tunnel. A droplet separation device collected the dispersed spray behind the test section. The resulting water film was directed back to the reservoir by means of shear and gravitational forces. Due to this procedure the conditions in the test section during the experiments can be very accurately controlled and reproduced.

In the present study, the wind tunnel velocity was always held constant at 20 m/s for the air flow. Two different spray properties, corresponding to two different operating modes for the pressure atomizer, have been investigated: A high pressure mode with 3 bar nozzle pressure provided a water volume flow rate of 5.4 l/min (Case 1); and a low pressure mode with 1 bar pressure and a volume flow rate of 3.3 l/min (Case 2). Both conditions correspond to rain properties near ground level.

Three different measurement techniques were used, in order to determine the size and the velocity of the droplets. The Shadowgraphy method and the Phase-Doppler Anemometry (PDA) are commonly used for such applications. Besides, a modified Laser-Doppler Velocimetry (LDV) technique in combination with an in-house developed software was used to carry out simultaneous velocity and size measurements. These different techniques correspond to different requirements, limiting measurement conditions and locations. The principles of Shadowgraphy and PDA are widely known and are therefore not described here. They can be found in the literature (e.g. [3; 4]). More interesting are the system specifications used during the experimental investigations.
The PDA measurements were carried out with a commercial Dantec Fiber-PDA system with specifications for the sending and receiving optics listed in Table 1.

<table>
<thead>
<tr>
<th>Sending optics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon-ion laser</td>
<td>150 mW</td>
</tr>
<tr>
<td>Wavelength</td>
<td>514.5 nm</td>
</tr>
<tr>
<td>Focal length</td>
<td>600 mm</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>1.35 mm</td>
</tr>
<tr>
<td>Beam spacing</td>
<td>18.5 mm</td>
</tr>
<tr>
<td>Beam expansion ratio</td>
<td>2.97</td>
</tr>
<tr>
<td>Probe volume</td>
<td>diameter=0.102 mm, length=2.226 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Receiving optics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of fringes</td>
<td>18</td>
</tr>
<tr>
<td>Fringe spacing</td>
<td>5.624 µm</td>
</tr>
<tr>
<td>Beam half angle</td>
<td>$\phi/2=2.622^\circ$</td>
</tr>
</tbody>
</table>

Table 1: System parameter of PDA sending and receiving optics

For the given system parameters the maximal measurable diameter was limited to a value of 2.2 mm. The size of the wind tunnel test section (1000x500x600 mm) constrains the focal lengths in sending and receiving optics. To ensure at all times an exact adjustment it was necessary to traverse all PDA components with one single traverse system (back-scatter). Thus, it was necessary to choose a large scattering angle ($161^\circ$) and to locate the receiver a few centimeters above the sending optics. This location of the receiving optics could only be used with second-order refraction, but was still below the critical angle of 164.9°. The standard BSA Flow Software was used for the PDA.

The shadowgraphy measurements were carried out with a standard CCD camera Imager Intense from LaVision and the associated software Davis version 7.1. A Questar QM-1 microscope (working distance from 550 mm to 1570 mm) was placed in front of the camera. The whole scene was illuminated with a double-pulsed Nd-YAG laser, filtered by a diffusing lens. The camera was placed on a separate traverse system on the opposite side of the wind tunnel. The illumination occurred from the side on which the PDA system was located.

Focusing the shadowgraphy camera onto the PDA/LDV-measuring volume was most important for comparative measurements. All three measurement techniques had to be conducted exactly at the same location inside the spray cone generated in the wind tunnel test section. The shadowgraphy calibration scale was placed in the measuring volume generated by the laser (LDV, PDA) and set to a fixed coordinate. For an adjustment of the measuring systems the shadowgraphy camera was focused exactly onto this point.

The LDV system is normally used for velocity measurements. Therefore, the same components were used as in the case of PDA measurements for sending optics. As a consequence the same measurement volume is of course obtained automatically. The LDV system parameters are listed in Table 1. The principle limitation of LDV (only velocity measurements) can be compensated with a special technique, called LDDV, developed at our Department [5]. The fundamental principle of this new LDV
application lies in the signal characteristics of particles passing through the measurement volume. Due to the fact that a burst can be separated into a low frequency part (pedestal signal) and a high frequency part (Doppler signal), it provides more than only the velocity information. The particle size measurement with the new software works in consecutive steps. During these steps the signals are acquired, separated into its pedestal and Doppler parts and evaluated online. Figure 2 provides an overview of the signal processing for the velocity and diameter estimation using a commercial LDV system and the complementary, in-house software for LDDV [5].

![Fig. 2: LDDV signal processing [5]](image)

The velocity estimation is carried out as usual by means of a Fast-Fourier-Transformation (FFT) and the particle size is determined in a separate way through the LDDV software. The pedestal samples run through a special algorithm, which starts with the definition of a “high threshold”-value. This value is adapted to the maximum signal peak. From the intersection points of the threshold level on the signal peak, it is possible to find the centre of the pedestal signal. Another “low threshold” value is chosen, to get rid of the background noise in the signal. This threshold value should be over the noise, but the smallest possible. When a particle larger than the measuring volume flows through this volume, the special structure of the pedestal shows two further signal peaks beside the maximum one. One is located before and one after the signal maximum, as shown in figure 3.
The two smaller peaks are intersected by the low threshold level. By this procedure, the middle of each peak can be found, which corresponds to two values for a certain time. The middle of the front peak defines the time at which the phase boundary at the front side of the particle (droplet or bubble) enters the measuring volume. This is the starting time \( t_1 \). The peak at the back of the pedestal signal occurs when the phase boundary at the end of the particle leaves the measurement volume. This yields the end time \( t_2 \). From the difference of the two times one can exactly calculate the travel time \( t \) of the particle through the measuring volume:

\[
t = t_2 - t_1
\]

It is then easy to calculate the diameter of the passing particle. Multiplying the transition time \( t \) with the velocity \( u \) gives the particle diameter \( d \).

\[
d = t \cdot u
\]

There is a practical limitation for the lowest measurable diameter, specified in the LDDV software during the signal processing, and associated to the width of the middle peak. In the present study, the lowest diameter limit was set to 150 \( \mu m \), which is suitable for the quite large droplets generated by the pressure atomizer in Cases 1 and 2 (simulated rain near ground level, i.e. large droplets).

A very big advantage of this measurement technique compared to PDA is that it does not require any separate receiving optics. It is therefore much easier to handle and does not lead to expensive investments, with the same capabilities for particles larger than the measurement volume.

As mentioned before two nozzle operating modes were investigated. In what follows, comparative measurements with all three methods at a central position within the spray cone will be shown. To obtain reliable statistics 5500 samples have to be acquired using point-wise laser measurement systems, as demonstrated by Lefebvre [6]. The number of images acquired by the Shadowgraphy system was set to 2500. Using the developed post-processing algorithm in the Davis software, this number leads roughly to the same number of particle measurements as in the case of PDA and LDDV.

3 Experimental Results

From the three measurement techniques local results for droplet velocity were obtained. The velocity results show for the high pressure mode (Case 1) the shape of a normal distribution around a mean
value of 17 m/s, as can be seen in figure 4. The same is observed for the LDV results of the low pressure mode (Case 2), around a mean value of 11.5 m/s, as shown in figure 5. PDA and shadowgraphy results deviate somewhat from a normal distribution in Case 2. This might be due to the higher relative velocity between the wind tunnel air flow and the dispersed droplets in that case, leading to higher deformations.

![Graph showing velocity distribution for high pressure and low pressure modes.](image)

**Fig. 4**: Velocity distribution (high pressure mode, Case 1)  **Fig. 5**: Velocity distribution (low pressure mode, Case 2)

Visually, all three velocity results match acceptably well, in particular for Case 2. The quality of the results can be quantified considering the statistical values shown in table 2.

<table>
<thead>
<tr>
<th></th>
<th>high pressure – p_w=3 bar (Case 1)</th>
<th>low pressure – p_w=1 bar (Case 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean velocity [m/s]</td>
<td>RMS [m/s]</td>
</tr>
<tr>
<td>PDA</td>
<td>17.39</td>
<td>0.94</td>
</tr>
<tr>
<td>Shadowgraphy</td>
<td>16.19</td>
<td>1.18</td>
</tr>
<tr>
<td>LDV</td>
<td>17.30</td>
<td>1.31</td>
</tr>
</tbody>
</table>

**Table 2**: Statistical values of the measured velocity distributions

Although the same laser system was used for PDA and LDV measurements, slight differences are still observed in the results. These are due to different software settings when using the commercial BSA Flow Software (for PDA) or the in-house LDDV software analysis. The mean values from PDA and LDV differ by less than 1 % for Case 1 and by less than 2 % for Case 2, which is almost perfect. Shadowgraphy shows a higher discrepancy compared to the PDA results, corresponding to 7 % for Case 1 and to 3 % for Case 2. This is still a very good agreement.

Simultaneously, results for the droplet size distribution were obtained as well and can be directly compared. The probability density functions (pdf) found from the results showed the shape of a log-normal distribution for all three measurement systems (see figures 6 and 7). Even if the values obtained from LDDV were a little bit shifted from the results of PDA and Shadowgraphy, the agreement is still quite acceptable. The deviation is mainly caused by the missing values below 150 μm, since particles
smaller than this size cannot be resolved accurately by LDDV. Considering this limitation, figures 6 and 7 prove that all three measurement techniques can be used to determine the pdf for both Cases.

![Fig. 6: Size distribution (high pressure mode, Case 1)](image)

Fig. 6: Size distribution (high pressure mode, Case 1)

![Fig. 7: Size distribution (low pressure mode, Case 2)](image)

Fig. 7: Size distribution (low pressure mode, Case 2)

The PDA and Shadowgraphy measurements gave nearly the same results, confirming other studies [7]. The agreement can be quantified by considering the parameters of the log-normal distribution function PDF($d_p$).

$$PDF(d_p) = \frac{1}{d_p \cdot \sigma \cdot \sqrt{2\pi}} \exp\left(-\frac{(\ln(d_p) - \mu)^2}{2\sigma^2}\right)$$

(3)

The parameter $\mu$ represents the logarithm of the count median diameter and was found to take values between 5.6 and 6.6. The variance $\sigma$ was obtained by fitting the PDF to equation (3) and was found to be in the range of 0.7 to 1. To quantify the differences, important statistical values were calculated and are listed in table 3.

<table>
<thead>
<tr>
<th></th>
<th>high pressure – $p_w=3$ bar (Case 1)</th>
<th>low pressure – $p_w=1$ bar (Case 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean diameter $d_{10}$ [µm]</td>
<td>RMS [µm]</td>
</tr>
<tr>
<td>PDA</td>
<td>428.96</td>
<td>19.41</td>
</tr>
<tr>
<td>Shadowgraphy</td>
<td>391.53</td>
<td>19.22</td>
</tr>
<tr>
<td>LDDV</td>
<td>845.58</td>
<td>23.07</td>
</tr>
</tbody>
</table>

Table 3: Most important statistical values of the measured size distributions

Considering figures 6 and 7 it was already clear that LDDV gave higher diameter results. This is due to the missing droplets, associated with diameter values below the LDDV threshold of 150 µm. Table 3 demonstrates that the difference is reduced for increasing droplet diameter, since the agreement is much better for Case 2 than for Case 1. Case 1 (high pressure mode) is associated with much smaller droplets. For case 2, PDA and shadowgraphy deliver almost identical results and the relative error obtained with LDDV stays below 20 %, which is quite good. Fortunately, Case 2 corresponds more
closely to realistic rain conditions near ground level and is therefore of higher interest. For all measurement systems and for both cases the RMS values of the diameter stay in the range of 20 $\mu$m.

Due to the fact that there is a fixed relationship between the Sauter mean diameter $d_{32}$ and the volume median diameter $d_{50}$

$$\frac{d_{32}}{d_{50}} = 1.1$$  \hspace{1cm} (4)

it is possible to check the consistency of the acquired data [7]. The correlation between these characteristic values show for the three measurement systems that all points lie within the tolerance of $\pm 10\%$.

![Figure 8: Correlation of Sauter mean diameter and volume median diameter](image)

When comparing the size distribution obtained with the different measurement systems the deformation of the droplets becomes an important question. PDA assumes the particles passing the measuring volume to be spherical; LDDV only measures the component of the particle diameter in the direction of the measured velocity. On the other hand, shadowgraphy can give information about the diameter ratio between the largest and smallest diameters and about the eccentricity of the present spray. Since the droplets are injected in the flow direction with a low velocity gradient between both phases, and considering that the system is very disperse (almost no collisions), the droplets stay mostly spherical, as confirmed by figure 9. Only the largest droplets show some deviation from a sphere.

![Figure 9: Typical shadowgraphy images for droplets of increasing diameter (from left to right and top to bottom)](image)
The dimensionless Weber number yields essential information about the droplet behaviour, deformation and secondary break-up:

\[ \text{We} = \frac{\rho_{\text{gas}} \cdot d \cdot v_{rel}^2}{\sigma} \]  

(5)

Different break-up regimes are associated with different values of the Weber number. The conventional classification is listed in Table 4.

<table>
<thead>
<tr>
<th>Weber number</th>
<th>breakup regimes</th>
</tr>
</thead>
<tbody>
<tr>
<td>We&lt;1</td>
<td>10% deformation</td>
</tr>
<tr>
<td>1&lt;We&lt;2.1</td>
<td>20% deformation</td>
</tr>
<tr>
<td>2.1&lt;We&lt;12</td>
<td>increasing deformation, exceeding 20%</td>
</tr>
<tr>
<td>12&lt;We&lt;50</td>
<td>bag breakup</td>
</tr>
<tr>
<td>50&lt;We&lt;100</td>
<td>bag and stamen breakup</td>
</tr>
<tr>
<td>100&lt;We&lt;350</td>
<td>sheet breakup</td>
</tr>
<tr>
<td>We&lt;350</td>
<td>catastrophic breakup</td>
</tr>
</tbody>
</table>

Table 4: Mechanisms of secondary droplet breakup and corresponding Weber values [8]

Since the information concerning droplet size and velocity was obtained simultaneously for all three measurement techniques, the corresponding Weber numbers can be computed for both cases. The results are presented in figure 10 for Case 1 (maximum Weber number below 2) and in figure 11 for Case 2 (maximum Weber number below 6). The theoretical results presented in Table 4 thus confirm that only a very small deformation (less than 20% for Case 1; slightly higher for Case 2) can be expected for the observed spray. All three measurement techniques lead to the same conclusions. For the conditions considered, the droplets stay almost spherical and break-up process are almost negligible.

![Fig. 10: Weber number correlation (Case 1)](image1)
![Fig. 11: Weber number correlation (Case 2)](image2)
4 Conclusions

The quantitative characterization of a spray in a two-phase wind tunnel was carried out by comparing three different optical measurement techniques: PDA, Shadowgraphy and LDDV (an extension of LDV). It was demonstrated that it is possible to obtain reasonably accurate results for the droplet velocity and size distributions using each of these methods. The best agreement is obtained between PDA and Shadowgraphy. But a quantitative diameter estimation is also possible using any commercial LDV system and the newly developed software LDDV. A comparison of the measured mean diameters showed an excellent agreement (difference smaller than 10 %) of the results coming from PDA and Shadowgraphy. The remaining, small discrepancy between PDA and Shadowgraphy might be due to deviation from sphericity, in particular for large droplets. The larger difference associated with LDDV comes from the fact that small particles cannot be measured. The difference is thus higher for high pressure atomization, when smaller droplets were generated. Nevertheless, LDDV remains very attractive for configurations containing large droplets, due to its simplicity and low cost. Shadowgraphy delivers supplementary information of high interest to quantify droplet deformation in the present conditions. It was shown that only a maximum of ca. 20 % deformation should be obtained for the investigated conditions. No droplet break-up was observed during the measurements, though droplets larger than 3 mm were sometimes present in the spray.

References


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