Deutscher Luft- und Raumfahrtkongress 2009
DocumentID: 121354

PERFORMANCE ANALYSIS OF DIFFERENT SHADOW SIZING CODES

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Abstract

Three shadow sizing codes for spherical as well as irregular shaped particles were compared. The comparison tests are based on five different test cases. An ideal test target with step-shaped boundary gradients (A), recorded images of this test target (B), images taken from a spray generated by a prefilming airblast atomizer (C), a dense spray dispersed in a carrier gas (D) and an image series of a falling droplet (E). The three codes under consideration are an in-house code from the Institute of Thermal Turbomachinery (ITS), the Shadow Sizer module, available as an add-on for Dynamic Studio from Dantec and DaVis-SizingMaster Shadow from LaVision. The results of the codes are compared on the basis of the number of detected particles, the detected diameter and the position. From the target tests it was found that the lower resolution limit of the ITS code enables the detection of particles represented by one pixel in the image plane, whereas for the commercially available codes – in line with their technical specifications – the lower resolution limit corresponds to particles having a diameter of 3 pixels. A similar result is obtained for the case of the airblast atomizer (B), i.e. the number of detected particles in one picture is the same for both codes for low, medium and dense sprays cases. Furthermore, the calculated droplet size distributions are in good agreement with each other, indicating size independent detection. For the measurements of droplet size distributions in the spray (D), the count based as well as the cumulative volume size distributions based on the ITS- and the DaVis-code agreed very well.

1. INTRODUCTION

The increasing availability of commercial image analysis software for aerosol characterization by means of shadow sizing for spherical as well as irregular shaped particles during the past few years necessitates a comparison of the capabilities and reliability of the different codes [6], [10]. In the present investigation, the performance and limitations of three shadow sizing codes for the analysis of shadowgraphy pictures have been tested in a joint research project between the Laboratory for Thermal-Hydraulics (LTH) at the Paul-Scherrer-Institute, Switzerland, and the Institute of Thermal Turbomachinery (ITS) at the University of Karlsruhe. The three codes under consideration are the commercially available DaVis-SizingMaster Shadow code (V7.2.1) from LaVision [2], Dantec Shadow Sizer (V1.45) and an in-house code from the ITS, [8], [9].

2. EXPERIMENTS

For the first test we analyzed a synthetic calibration target (A). This target was drawn using a graphics program script, with the resulting TIFF image having step-shaped, sharp boundary gradients. The advantage of a calibration slide is the a priori knowledge of size and location of the particles. The calibration slide provides ideal conditions for a first analysis. The disturbances imposed by the optical setup can be neglected. With the synthetic calibration image, figure 1 top, the LaVision software SizingMaster and the ITS-Matlab-code were tested. The analysis using the Dantec software Shadow Sizer failed since the large file size of 6193×3180pixel caused an out-of-memory error.

For the next step, the synthetic image was printed on a foil, fixed in the focal plane, backlight illuminated and recorded with a digital camera, PCO SensiCam, (B) figure 1 bottom. Printing of the slide was done in a repro studio with a Heidelberg DI press on a transparent film. One pixel on the printed slide corresponds to 5 µm on the film; this is equivalent to 5080 dpi resolution. With the recording system used one pixel on the printed slide corresponds to 0.2 pixel on the CCD-chip, or the other way round, one pixel on the CCD-chip corresponds to 25.9 µm on the foil.

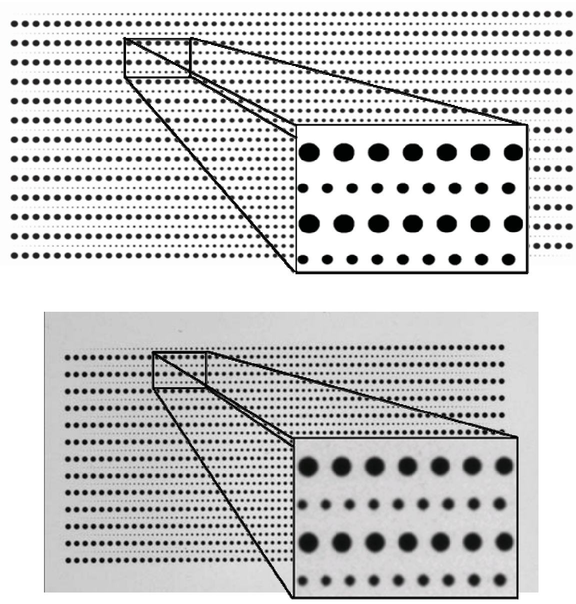

Figure 1: Synthetic calibration target with 76 particles in 26 rows (top) and image of the printed and recorded calibration target (bottom).

Using opaque disks on the calibration slide instead of transparent spherical particles (droplets) in reality causes no loss of generality. As the particles are much larger than

the wavelength of the laser light used for backlight illumination, the shadow images of the particles are similarly diffracted. Therefore, the shadow images resulting from a sphere and a disk having the same radius are considered the same [3].
The real world images analysed for the third case (C) have been recorded in the vicinity of an prefilming airblast atomizer simulating the fuel injection into a combustion chamber, figure 2.

Figure 2: Airblast atomizer image. Air flow is from top to bottom

In contrast to a real airblast atomizer used in gas turbines and aero engines the present setup is simplified. Despite the fact that in real airblast atomizers the airflow is concentric and swirling, but in the experiment the air flow is planar, the experiments are designed such that the film disintegration and spray generation are comparable. One pixel on the recorded images corresponds to 25.3 µm in reality, which is the same magnification as for the calibration slides described above. A more detailed description of the experimental setup and the results can be found in [8] and [9].
The second real world image series (D) was recorded in a very dense spray after the conditioning section and before the droplets enter the swirl vane unit of a steam generator, figure 3.

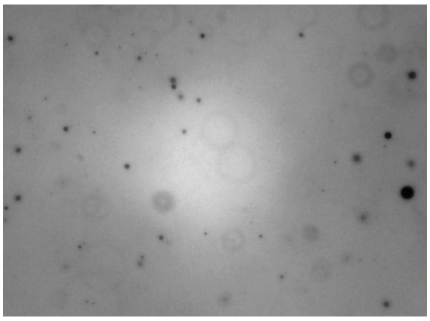

Figure 3: Dense spray in a steam generator.

The spray is generated by a twin fluid, air-assist, full cone spraying nozzle. Due to the spray density the backlight illumination of the images varies with measurement position and many defocused particles influence the analysis results. In addition to the image analysis, the droplet measurements from the steam generator were complemented with phase-Doppler anemometer (PDA) measurements for the same conditions. The operation principles of the PDA system can be found in [1]. For details of the PDA setup see [5].
Finally, with test type E, an image series of falling droplets was analyzed to test the position detection capabilities of the LaVision Sizing Master and the ITS-Matlab-code.

3. ANALYSIS PROCEDURE

For the present experiments the analysis of the images can be described as a 4-stage process. The first step consists in image pre-processing operations, the second in separating the objects from the background and detecting the different objects in each picture, the third step in calculating the droplet size and the fourth step in different filter operations to exclude for example out-of-focus particles.
The first step in the DaVis software is optional image preprocessing. Possible filter operations to correct the images are, for example, a moving average, a mean filter and a peak filter. Pre-processing also includes the correction of an inhomogeneous illuminated background by means of a reference image. This reference image is also necessary to calculate an inverted image. The inverted image G' is calculated by subtracting the particle image G_{raw} from the reference image G_{ref}. The reference image is an illuminated image of the background without particles. The image segmentation is performed with a global threshold such that all intensities *below* the global threshold are not taken into account. This global threshold is defined as a certain percentage of the difference between maximum and minimum intensity in the inverted image and is a user selectable parameter. Please note, that with this definition, the threshold value is reversed compared to thresholds defined for non-inverted images (ITS-code).
In a refined segmentation, areas with a higher intensity than the global threshold are now analyzed locally such that a bounding box F_1 is formed around an area of pixels with gray values above the global threshold, figure 4.

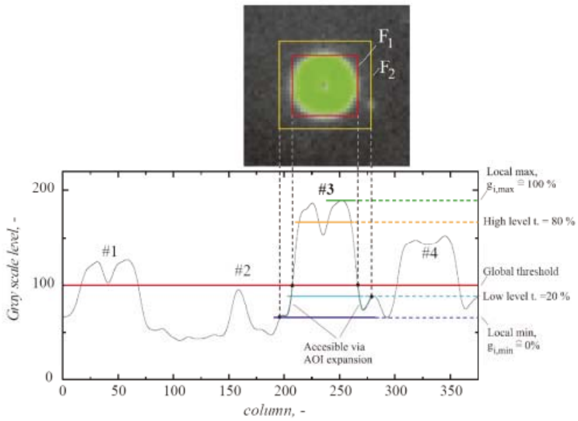

Figure 4: Global and local segmentation procedures as applied by the DaVis software, picture taken from [6].

With the user selectable value for the "AOI expansion" (area of interest) a second larger box is set up around the first bounding box. The default value for the AOI expansion is 50 %, i.e. the area of F_2 is 50 % larger compared to F_1. Within the AOI expansion box the local minimum and the local maximum intensities are determined. These two extremes define the 0 % and 100 % limit for the second, local segmentation. To calculate the size of the particle, the areas segmented at the low level threshold and the high level threshold are identified. The default values for the low and high thresholds are 40 and 60 %, respectively. For the segmented regions at the low and the high level thresholds circles are approximated such that these regions are just contained in these circles. From these two circle diameters a mean particle diameter is calculated. If

the AOI expansion is chosen too small the calculated size of the particles will be incorrect, because the local 0 % intensity is detected too high in relation to other particles. Using the low and high threshold together with a comparison of the radii calculated might serve as an implicit out-of-focus criterion since out-of-focus particles will experience a larger radii difference compared to in-focus particles.
The Shadow Sizer feature is an add-on to the software Dynamic Studio from Dantec. The correction of images by means of a reference image is not implemented in this software. However, this can be done prior to the analysis with an image arithmetic step. The first step in the analysis software 'shadow processing' consist in segmenting the image, i.e. to separate objects from the background. As for the previous software described above, this is done by applying a global threshold where the threshold level can be adjusted by the user. The value of this threshold level is set in terms of a percentage value based on the maximum grey level appearing in the image. For the appropriate selection of the threshold value the user is assisted by a so called 'shadow assistant'. Within this assistant one can choose a small section of the image which must contain at least one particle which is regarded as being representative for the whole set of particles. For the selected particle the threshold is calculated either by an auto-select function or set directly by the user. In addition to the threshold value, the parameters height and slope of an edge can be displayed for validation purposes. The edge heights validation calculates the intensity difference from a local minimum to a local maximum of a particle edge, expressed as the grey level percentage of the grey level range of the image format. The edge slope validation determines the slope of the grey level gradient of the particle at its borders. The value is calculated by fitting a curve to the edge of the particle crossing the threshold cut-off. These values are calculated for the minimum and for the maximum diameter line. These two restrictions - the edge heights and the edge slope validation - represent Dantec's out-of-focus criteria. These two criteria are used to reject particles which have too small contrast with respect to the background as well as too low grey level gradients at the particle boundaries. One might easily run into trouble with these criteria since they reject not only particles that are out-of-focus but also very small particles, see figure 5.
As for Dantec's software, the Matlab based ITS-code expects raw images with an already homogeneous background as input, i.e. the particle shadows appear black on a bright background. Particle segmentation with the ITS-code is done with the image histogram information. For the segmentation, i.e. the separation of the objects from the background, it is assumed that most of the histogram represents the background intensity. The threshold is now defined in relation to the median of the histogram and the zero intensity in the image. Zero intensity is defined as 0 %, and the median of the background intensity as 100 %. For the segmentation of the background and the objects the threshold is defined as 80 %. This value of 80 % is the default value but can be changed for other purposes. Experiences have shown that this threshold is appropriate for almost all test cases but it should be noted that the size of the particles is not detected correctly. According to [7] the real size of a particle can be found somewhere around a threshold value of 50 % with respect to maximum grey level of a particle. Despite this, the threshold was chosen as 80 % since more of the smaller particles can be detected using a higher threshold although the corresponding particle diameter is wrong. Consequently, with the standard procedure, particles are detected too large and small particles with a diameter below 3 pixel are detected too small, when using a threshold of 80 %, figure 5.

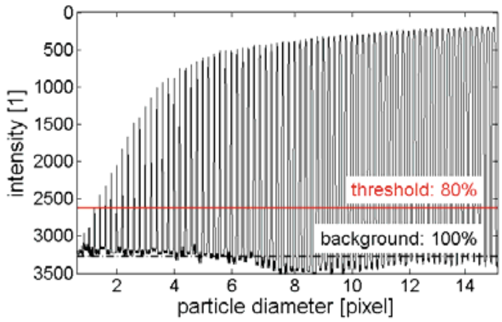

Figure 5: Intensity modulation along a horizontal line extracted from the recorded calibration target, figure 1.

This deviation has to be calibrated. After the segmentation, the program generates an image with the outlines of the particles as detected from the threshold of 80 %. Such outlines are made up of several vertices according to the number of pixels the particle consists of. To be detected as a valid particle, at least 5 vertices are needed for the outline. Through these vertices an ellipse is fitted. With the two semi axes of the ellipse the equivalent volume of an ellipsoid is calculated, taking the shorter diameter as diameter in the depth. From that volume of that ellipsoid the equivalent volume of a sphere is calculated. This sphere volume is regarded as the particle volume and the equivalent particle diameter can be calculated.

4. RESULTS

4.1. Target Tests

For the analysis of the synthetic image target tests (A) it is necessary to assign the detected particles to a 'particle class'. A particle class is designated by the 26 particles having different diameters on the slide. Since the position of each particle on the slide is a priori known, it is possible to assign each detected particle to its corresponding particle class. With this procedure it is possible to compare the accuracy of the different software codes in detecting the diameters of the particles and to detect systematic errors in the sizing algorithms.
The results of this comparison can be found in figure 6 for the DaVis- and ITS-code; the Dantec code failed since the large file size caused an out-of-memory error as already mentioned earlier. Since the synthetic calibration slide i) only contains the grey values 0 and 255 and ii) the gradient at the edge of the particles is accordingly steep the different setting of the global threshold in Davis Sizing Master and ITS-Matlab-code has no influence on the particle detection. The smallest particle the SizingMaster code can detect has a diameter of 3 pixel as stated in the manual. Accordingly, the three smallest particle classes are not detected. In contrast to this, the ITS-code detects particles down to a size of 1 pixel. Whereas the results of the analysis with LaVision SizingMaster show a good agreement with the real size of the particles, the ITS-Matlab-code over-predicts the diameter systematically by 0.6 pixel.

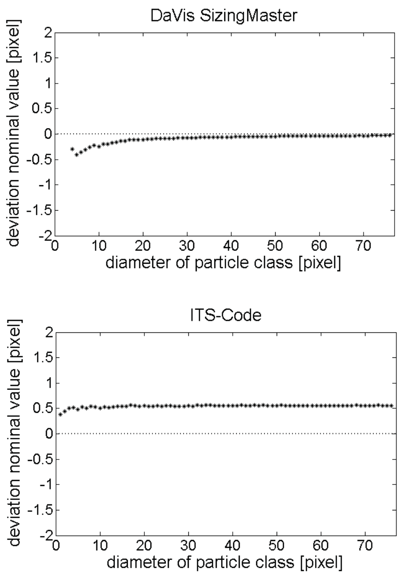

Figure 6: Deviation of the calculated diameter from nominal diameter for the synthetic calibration target.

The reason for the latter over-prediction can be found in the threshold definition implemented in the ITS-Matlab-code. The Matlab routine calculates the gradient from pixel centre to pixel centre by which the code generates a gradient that is no longer a step function as in the original pixel graphic. Consequently, the diameter of the particles is calculated too large. The discussion of other aspects like the number of detected particles in each particle class and the diameter standard deviation within each particle class are beyond the scope of this article and the interested reader is referred to [10].

The results from the analysis of the recorded calibration target (B) are shown in figure 7 and figure 8. The number and size of particles detected for each size class are shown in figure 7. It is found that the standard deviation for the DaVis-code is below 0.1 pixel. This excellent value corresponds to the expected value for the deviation in image recognition processes as stated in [4].

For Dantec's software, the values are higher, at about 0.3 pixel. The reason for this high standard deviation can probably be found in the discrete steps of diameter values calculated by the Shadow Sizer. This leads to a large error in the diameter calculation especially for small particles. For the medium-sized particles the ITS-code shows good results for the standard deviation of 0.1 pixel, whereas the standard deviation for smaller and larger particles increases to 0.25 Pixel. This increase is caused by the changing background grey scale levels of the calibration image. A slight variation of the background illumination can be seen between the right and the left side of the image [10]. Since the small and the large particles are located in these inhomogeneous illuminated regions, the standard deviation of the diameter increases. In contrast to this, it was found that the background intensity for the medium-sized particles in the middle of the image is almost constant; consequently, the standard deviation of the diameter is accordingly low. Since the global threshold in the ITS-code also defines the size of the particles this method is vulnerable to inconsistent background intensity.

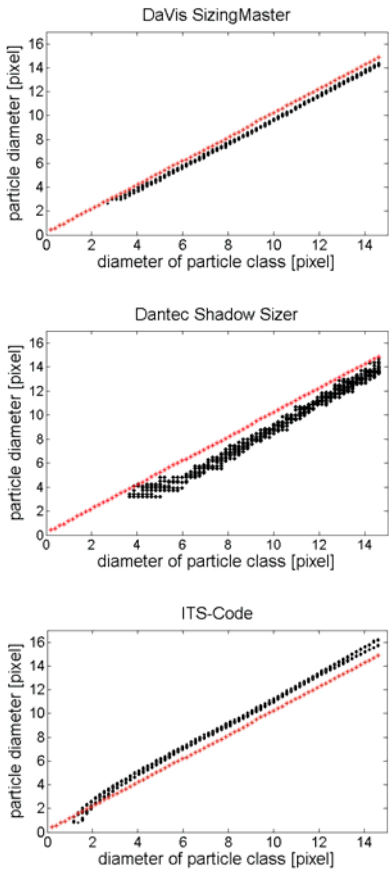

Figure 7: Number and size of particles detected for each size class for the recorded calibration image.

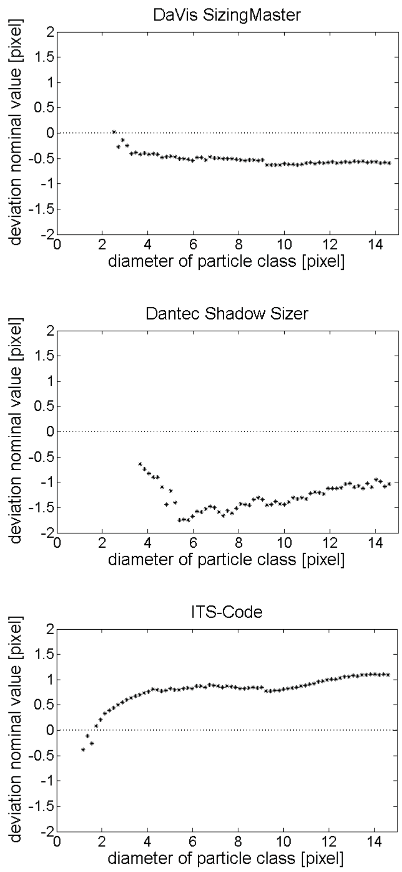

Figure 8: Deviation from nominal value as a function of size class for the recorded calibration image.

The deviations from the nominal particle size in each class are presented in figure 8. Comparing these results with figure 6 the influence of non-ideal recording conditions becomes apparent. For the SizingMaster the particles are detected about 0.5 pixel too small. Except for the smallest particles, this deviation remains constant independent of the particle size. This effect can be attributed to the second thresholding-step implemented in the SizingMaster code, i.e. the two additional local thresholds from which the size of the particle is calculated independently from the global threshold. Adjustment of the local thresholds would solve for this problem, but emphasizes an appropriate calibration. Dantec's Shadow Sizer also detects the particles too small but with an increased magnitude of 1 to 1.5 pixel compared to the DaVis-code. For particles with diameters above 4 pixel, the ITS-code detects the particle size about 1 pixel too large. For particles of about 2 pixel, the diameter is detected correct and smaller particles are detected too small; this is in-line with the explanation given above, see figure 5. Since the Shadow Sizer works with a global threshold defining simultaneously the image segmentation *and* the size of the particles, one would expect a similar shape as for the ITS-code; but the shapes of the curves differ considerably. The reason for this might be the global threshold differently defined for both programs and adjusted to different values. The deviation from the nominal value for the ITS-code has its simple reason in the global threshold set at 80 % of the median of the image histogram. Larger particles experiencing a very low grey scale level are detected too large because the particle size is detected at the 80 % threshold cutting those particles at the lower part of the grey level peak. On the other hand smaller particles do not reach the minimum grey level of the image as larger particles do, such that their size is detected in the middle or at the top of their grey level peak. This leads to a correct or too small detected particle size, as shown in figure 5.

4.2. Prefilming Atomizer Tests

It was shown in a previous section that the ITS-code can detect particles down to a diameter of 1 pixel, whereas the DaVis- and the Dantec-code can detect particles only down to size of 3 pixel. The number of particles detected for 5 different images recorded in the prefilming atomizer tests (C) were compared in figure 9 (top) without considering this topic and in figure 9 (bottom) where particles below 3 and above 25 pixel were excluded from the analysis. If one restricts the analysis to the size range all three codes 3 to 25 pixel, one finds a very good agreement for the detected number of particles irrespective of the image used.
In contrast to this, figure 9 (top) shows the large amount of additional small particles, that were detected by the ITS-code. Small particles with a diameter of 1 to 3 pixel have a pronounced influence on the number of detected particles but not on the total particle volume. The volume is – for example – the most important quantity for the estimation of correct fuel injection or steam generation. The corresponding cumulative volume distributions for two representative airblast atomizer images are shown in figure 10 (top, image no. 3) and in figure 10 (bottom, image no. 2) with considering the measurement range. Despite confining the measurement range, the ITS-code detects more larger particles compared to the other codes.

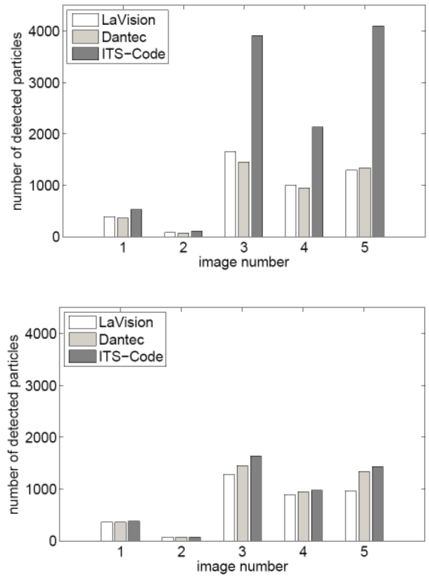

Figure 9: Number of detected particles for 5 different images recorded for the prefilming atomizer tests. All detected particles considered (top), only particle with a diameter within 3-25 pixel (bottom) considered.

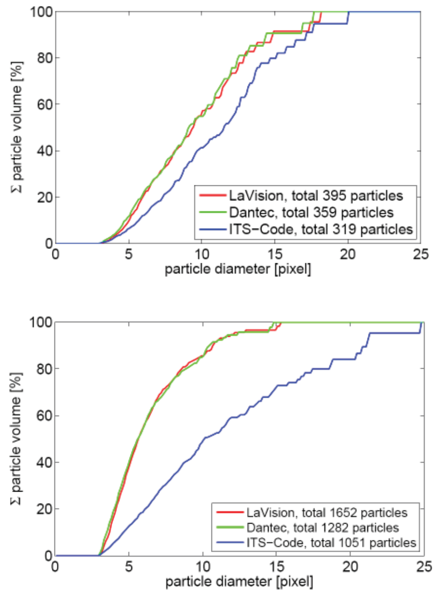

Figure 10: Cumulative volume distribution for image no. 1 (top) and no. 3 (bottom).

In contrast to small particles, a small number of large particles has a large influence on the cumulative volume distribution as is presented in figure 10 (top).
An explanation for the larger particles detected from the ITS-code could be that image no. 3 contains a large overall number of particles such that many of them are located very close to each other or even overlap in the projection. The ITS-code tends to count these optically merged particles as one particle and fits a flat ellipse over these particle agglomerates, whereas the commercial codes exclude these particles from the analysis according to additional roundness criteria.

4.3. Spray tests

The spray tests (D) were performed through plane glass windows at three different vertical positions in a cylindrical Perspex tube with an inner diameter of 500 mm. The coordinate system has its origin in the symmetry-axis of the test section. The droplets are generated by means of a twin-fluid atomization, air-assist, full cone spraying nozzle projecting upwards in the axis of the test section. The spraying nozzle orifice is located 1.6 m below the measurement position. The droplets generated are transported by a carrier gas through the test section. The cumulative volume distributions measured by means of shadowgraphy and a phase-Doppler anemometry system (PDA) are presented for two horizontal positions (x=0 and x=200 mm with P200) in figure 11.

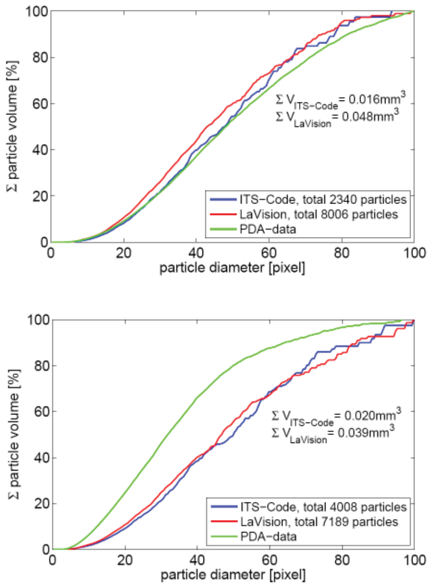

Figure 11: Cumulative volume distribution for spray tests at the position x=100 mm (top) and x=200 mm (bottom) from the tube axis.

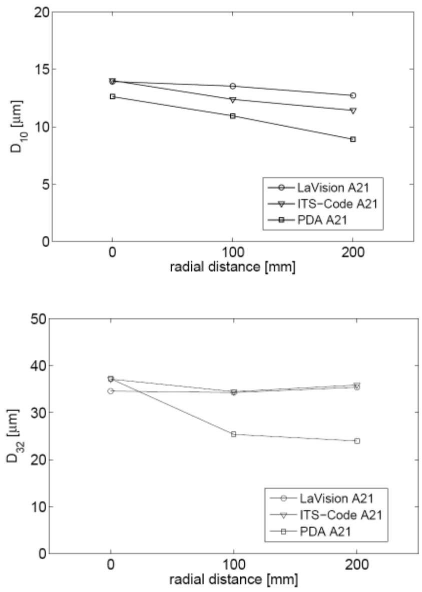

Figure 12: Count mean- and Sauter-diameter for spray tests at position x=100 mm (top) and x=200 mm (bottom) from the tube axis.

The Shadowgraphy results were analyzed with the DaVis- as well as with the ITS-code. For the DaVis- and ITS-code based results there is an excellent agreement for the cumulative size distributions as well as for the derived count mean diameter, D_{10} and the Sauter-mean diameter, D_{32}, irrespective of the horizontal position and irrespective of the droplet-size distributions generated, not shown here but in [1]. Additionally, for the in-axis position (x=100 mm), we find a good agreement with the PDA-based results, whereas there is a considerable difference for the outer positions which is especially reflected by the Sauter-mean diameter, figure 12 bottom. This difference is subject to further discussions and might result from the Shadowgraphy- as well as from the PDA-setup.

4.4. Particle Position

The previous sections were concerned with the size of the particles. Another aspect is the detection of the position of the particles. A treatment of this aspect would be possible with the calibration image by comparing the detected particle positions with the particle pattern of the calibration target. An alternative approach to analyze the precision of the position detection of the Codes is to analyze a series of 175 images of a falling droplet and to compare the velocity calculated from each successive image-pair.

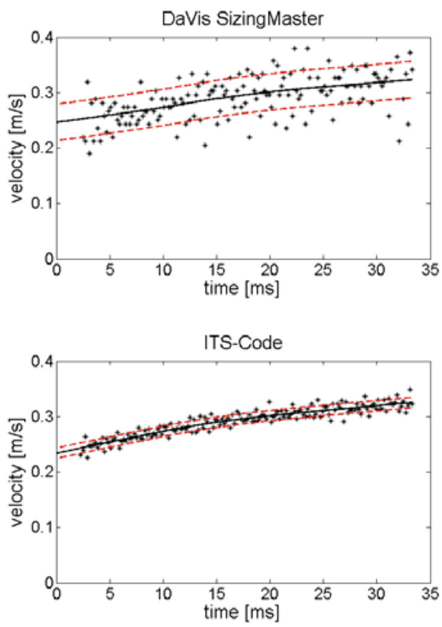

Figure 13: Droplet velocity in y-direction calculated from position detection for the DaVis Sizing Master (top) and the ITS-Matlab-Code (bottom).

Acquisition was done during another student research project at the ITS with a recording frequency of 5 kHz, which equals one image every 0,2 ms. One pixel on these images corresponds to 12 µm in reality. This image series was analyzed with the LaVision SizingMaster and the ITS-Matlab-code. The position of the droplet was calculated for each frame and – together with the time of the recording sequence – a differential quotient results in one velocity value for each image pair. The resulting velocities for the two software analysis results are shown in figure 13.

Since the time base is the same for both results it becomes obvious, that the position detection is more precise for the ITS- compared with the DaVis-code. These graphs illustrate the importance of the precise detection of the particle position. The standard deviation for the velocity (marked as red line) in y-direction amounts to 2.7 pixel/ms (=33 mm/s) for the SizingMaster and 0.8 pixel/ms (=9 mm/s) for the ITS-code.

5. IMPROVEMENT OF THE ITS-MATLAB-CODE

During this work it became more and more apparent how important a homogeneous background of a shadowgraphy image is, especially for the analysis of the recorded calibration image. Usually the inhomogeneous background of the image is corrected during the acquisition by subtracting a so called white image. But still the background is not completely corrected due to the pulse-to-pulse, radial intensity variation of the laser light. This can not be corrected during the acquisition because reference image and particle image are recorded during two different laser pulses.

The first method implemented to correct for inhomogeneous illumination in the ITS-Matlab-code was the option to import a hand adjusted reference image. This procedure was tested using a reference image with five different grey scale levels arranged in vertical stripes. With this approach it was possible to considerably lower the formerly large difference in background illumination between the left and right side of the calibration image. For images treated with this additional reference image, the standard deviation for the smaller and larger particles are significantly smaller but remained the same for the medium-sized particle classes. The next step of improvement was to apply a median filter to the recorded image. This median filtered image was then subtracted from the calibration image and this calibration image was used to homogenize the particle image. The effect of the latter approach is pictured in figure 14.

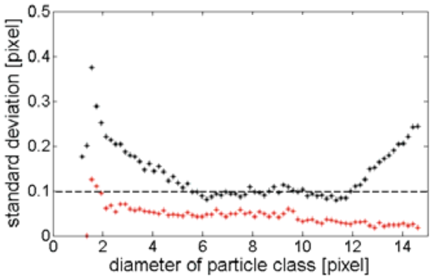

Figure 14: Particle size standard deviation in each particle class for an image background corrected with the reference image generated by median filter.

Compared with the untreated reference image (black) the result of the background correction (red) is striking. The standard deviation drops below the theoretical value of 0.1 pixel.

6. SUMMARY

The performance of three image analysis codes for aerosol characterization using shadowgraphy images was tested with five different test cases. From the target test (A) it was found that the lower resolution limit of the ITS-code permits the measurement of even the smallest possible particles of one pixel, whereas for the commercial DaVis- and Dantec-software the lowest particle detection limit amounts to particles with a diameter of three pixels. With the recorded calibration target (B) it was demonstrated, that the ITS-code is less robust with respect to background inhomogenities compared with the DaVis-software and that the local threshold-adjustment in the DaVis-software necessitates the use of calibration targets to adjust for the correct particle diameters. By limiting diameters to the same dynamic range for the three codes, a good agreement for the number of detected particles could be achieved for the prefilming airblast atomizer images (C). The cumulative size distribution for low-density shadowgraphy images is excellent, whereas this size distribution for high density images differs considerably. The spray based results (D) demonstrate an excellent agreement for the DaVis- and ITS-based results with respect to the cumulative volume size distribution as well as for the count mean and Sauter mean diameter. The agreement with PDA-based results show a strong position bias, i.e. the comparison in the axis of the test section is good, whereas one finds considerable differences for out-of-axis positions. Analysing the position detection of particles (E) led to good results for the ITS-code in comparison to the standard deviation of the results obtained with the DaVis SizingMaster.

The tested Dantec software Shadow Sizer was released in 2007. We want to thank Dantec for providing it free of charge. Now (2009) many of the suggested improvements are included in the latest version.

[1] Albrecht, H.-E. and Borys, M. and Damaschke, N. and Tropea, C. (2003), Laser Doppler and phase Doppler measurement techniques. Springer-Verlag.
[2] Berg, T., Deppe, J., Michaelis, D. Voges, H. and Wissel, S. (2006), Comparison of particle size and velocity investigations in sprays carried out by means of different measurement techniques, ICLASS-2006, Aug 27 - Sept 1, Kyoto, Japan, paper ICLASS06-151.
[3] Blaisot, J. B., Yon, J. (2005), Droplet size and morphology characterization for dense sprays by image processing: applications to the Diesel spray, Experiments in Fluids, Vol. 39, pp. 977-994.
[4] Brand, P. and Mohr, R. (1994), Accuracy in image measure, SPIE, Videometrics III, pp. 218-228.
[5] Kapulla, R., Trautmann, M., Sanchez, A. H., Zaragoza, S. C., Hofstetter, S., Häfeli, C. Güntay, S. (2007), Droplet size distribution measurements using phase-Doppler anemometry and shadowgraphy: Quantitative comparison, Lasermethoden in der Strömungsmesstechnik, 15. Fachtagung, Rostock.
[6] Kapulla, R., Tuchtenhagen, J., Müller, A., Dullenkopf, K., Bauer, H.-J. (2008), Droplet Sizing Performance of Different Shadow Sizing Codes, Lasermethoden in der Strömungsmesstechnik, 16. Fachtagung, Karlsruhe.
[7] Kim, K. S. and Kim, S. S. (1994), Drop Sizing and Depth-of-Field Correction in TV Imaging, Atomization and Sprays, Vol. 4, 65 – 78.
[8] Müller, A., Hehle, M., Schäfer, O., Koch, R., Bauer, H.-J. (2005), Zerstäubungsverhalten von Airblastdüsen bei oszillierenden Strömungen, VDI-Bericht Nr. 1888, 22. Deutscher Flammentag, September 21 - 22, Braunschweig, pp. 249-257.
[9] Müller, A., Hehle, M., Schäfer, O., Koch, R., Bauer, H.-J. (2006), Performance of Prefilming Airblast Atomizers in Unsteady Flow Conditions, ASME Turbo Expo 2006, May 8 - 11, Barcelona, Spain.
[10] Tuchtenhagen, J. (2008), Untersuchung der Leistungsfähigkeit verschiedener Methoden zur Schattenbild-Auswertung, Diplomarbeit, Institut für Thermische Strömungsmaschinen, Uni Karlsruhe (TH).