

Optimization of defocused particle sizing methods for continuous measurement of high flux and concentration conditions of the disperse phases

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ABSTRACT

The characterization of dispersed multiphase flows requires measurement techniques capable of determining particle concentration, size distribution, and particle type under realistic operating conditions. This work presents an advanced implementation of the Hydrodynamic Nuclei Concentration Technique (HDNC), a defocused imaging method for the simultaneous detection of bubbles and solid particles in liquid flows.

Particle sizing is performed by analyzing interference structures within defocused particle images generated by coherent laser illumination. While spherical particles are characterized using fringe frequency analysis, non-spherical particles are evaluated through their speckle structures. To enable measurements at elevated particle concentrations, a square aperture design is introduced, providing improved particle separation and computationally efficient signal processing. In combination with statistical detection-volume correction, the approach allows reliable estimation of particle concentrations and size distributions under high-throughput conditions.

The performance of the method is demonstrated using measurements in the K21 cavitation tunnel at the University of Rostock. Time-resolved results reveal the dynamic evolution of bubble concentration and bubble size during controlled bubble injection, including transport delays and dissolution effects relevant for cavitation studies.

The presented technique enables continuous and real-time capable characterization of dispersed multiphase flows and provides a foundation for future environmental monitoring applications, including e.g. the detection and quantification of microplastic particles in water.

1 Introduction

There are a number of optical in-situ measurement techniques for characterizing dispersed phases in multiphase flows. In flow measurement technology and for chemical reactions, the concentrations, fluxes, and size distributions of the dispersed phases are relevant, as the ratio of volume to surface area depends strongly on the size distribution. The measurement techniques

must therefore characterize individual particles and calculate the relevant statistical measures from these.

A classic measurement technique is the phase Doppler (PD) technique (Albrecht et al. 2003). However, it can only characterize spherical particles and is limited to one dispersed phase. The PD technique is a point measurement technique and requires long measurement times because the dispersed flow field must be sampled point by point in sequence. Therefore, PD technique can only be used for stationary two-phase flows.

Interferometric laser imaging droplet sizing (ILIDS) also called interferometric particle image velocimetry (IPI) was developed for multidimensional particle detection (e.g. Kobayashi et al. 2000, Damaschke et al. 2002). It uses defocused images of particles illuminated by a laser light sheet (see Figure 1). Based on the interference structure within the defocused images the size of the spherical particles can be determined, as the scattering characteristics of the particles are known. Furthermore, spherical and non-spherical particles can be classified using the structure of the interference fringes (e.g. Brunel et al. 2014).

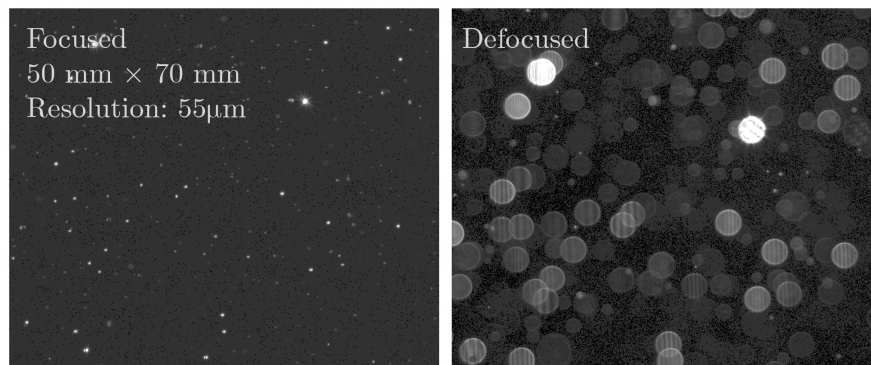


Figure 1 Focused (left) and defocused (right) multidimensional imaging of particles (Damaschke et al. 2005)

This opens the possibility of characterizing multiphase dispersed flows as well. Examples are flows in maritime applications, which generally contain both bubbles and solid particles. Typically, the concentration of solid particles in maritime applications is comparable to or even higher than that of the bubbles.

In the technical field, bubbles act as cavitation nuclei. The prediction of cavitation is thus dependent on the bubble concentration in the cavitation tunnel and, consequently, on the operating point. In natural processes, for example, oxygen entry correlates with bubble concentration and size distribution. A further intended application is the detection of microplastic

particles in water. (Merck et al. 2025). The number of microplastic particles is very low compared to many organic, inorganic particles and bubbles ($< 1:10000$). Continuous high-throughput measurements are necessary for quantitative flow and concentration measurements of the dispersed phases (number concentration, volume concentration, surface concentration). This requires real-time evaluation with specialized sensor systems, e.g., smart camera systems, which is available from other applications (Steinmetz et al. 2023).

2 Measurement technology

2.1 Measuring principle

The measurement principle is based on the scattering of coherent laser light by particles. In direct imaging techniques, the scattered light is focused onto the image sensor by a lens, producing a sharp image of the particle (see Figure 2).

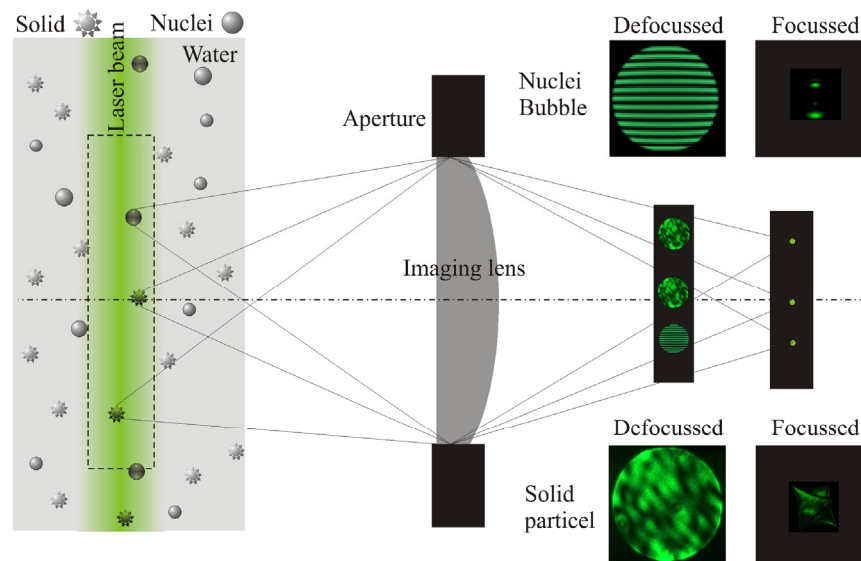


Figure 2 Principle of HDNC measurement technique (Ebert 2015)

For particle size determination from focused images, the spatial resolution of the imaging system must be sufficiently high so that the particles are imaged over several pixels. Due to the limited number of pixels, this results in a small measurement volume (e.g. microscopy). With defocused images, the measurement volume and size determination can be decoupled from one another. The position of the defocused image corresponds to the position of the particle in the process and is defined by the imaging properties of the optics used. The particle size and other properties can be

determined from the interference pattern within the defocused image. The extent of the defocused images can be adjusted via the degree of defocusing. The scattering angle range captured by the aperture defines the resolution for size determination and is thus largely independent of the spatial resolution for position determination. However, this decoupling results in an overlap of the particle images at higher particle concentrations (see Figure 1 right).

2.2 Relation between interference and particle size

Particle size determination is based on the interference of the glare points that scatter toward the receiver. The defocused image on the sensor directly corresponds to the scattered light intensity within the lens's aperture and thus represents the scattering function of the particle.

Figure 3 shows, on the left, an example of the scattered light intensity from a spherical bubble in water with a diameter of 50 μm at a wavelength of 532 nm for both polarizations (upper and lower graphs). The glare points produce an angle-dependent interference pattern with varying frequencies.

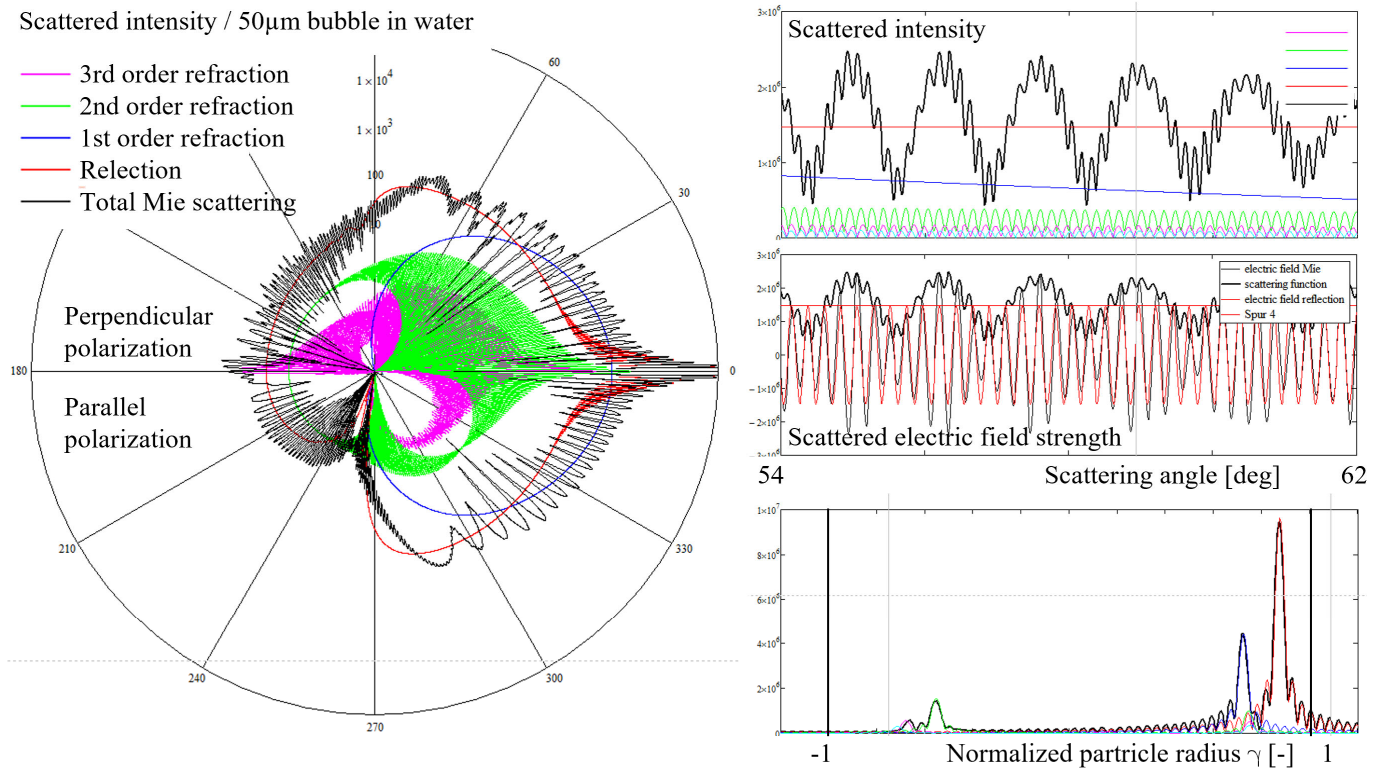


Figure 3 Scattered light intensity for a 50- μm bubble in water. Left: Total scattered light intensity; Right: Scattered light intensity, electric field strength, and reconstructed glare points for an angular range.

Furthermore, the intensity and modulation depend on the scattering angle ϑ and the polarization. The angular frequencies are a direct measure of the distance between the glare points and thus of the bubble diameter (two-point interference).

For a specific application, the interference pattern must be optimized in terms of measurement range, working distance, aperture size, and intensity. The normalized distance between the glare points (Figure 3, bottom right) can be calculated from the Fourier transform of the angle-dependent scattered light (Figure 3, middle right). The width of the reconstructed glare points is due to the limited aperture and gives the point spread function of the imaging system. Figure 4 shows the radial glare point positions γ and intensities, normalized to the bubble radius, plotted as grayscale values as function of the scattering angle for both polarizations.

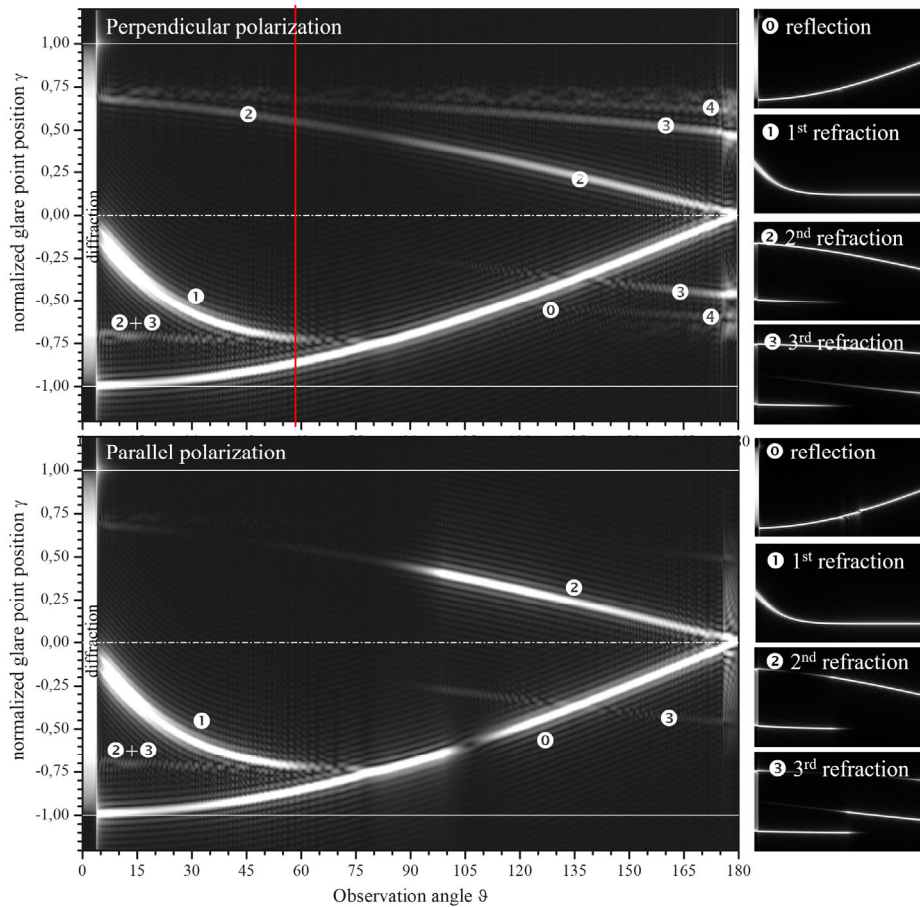


Figure 4 Calculated normalized radial glare points positions for an air bubble in water for both polarizations (left) and separated scattering orders (right). The case used in Figure 3 is marked by a red line

The ideal setup for spherical particles is two glare points of maximized and equal intensity and with large angular separation $\Delta\gamma = \gamma_1 - \gamma_2$. For bubbles, this condition is nearly ideal at a

scattering angle of 90° , with the drawback that the glare points from reflection and second-order refraction do not have the same intensity. This reduces the depth of modulation of the interference fringes. The advantage, however, is that the camera can observe the light sheet or measurement range at 90° without perspective distortion and without changing the defocus.

If the normalized glare points distance $\Delta\gamma$ is scaled by the particle size d_p and known wavelength λ , the result is the angular frequency of the interference fringes. The detected scattering angle range $\Delta\vartheta$ is defined by the aperture size and aperture distance and therefore the Number of fringes is a direct measure of the particle diameter

$$N_F = \frac{\Delta\vartheta\Delta\gamma}{\lambda} d_p$$

Compared to geometric optics, the approach presented here, which utilizes Mie scattering, provides both highly accurate conversion factors and information on disturbing interference caused by higher-order focal points.

A similar approach can also be applied to non-spherical, rough particles with many glare points. Small particles with closely spaced glare points produce large speckle structures, and large particles produce small speckles. Figure 5 shows examples of simulated defocused images based on diffraction theory and real defocused images. The particle shape cannot be reconstructed, but the maximum particle size as seen by the receiver can be estimated (e.g. Brunel et al. 2014, Steinmetz et al. 2018).

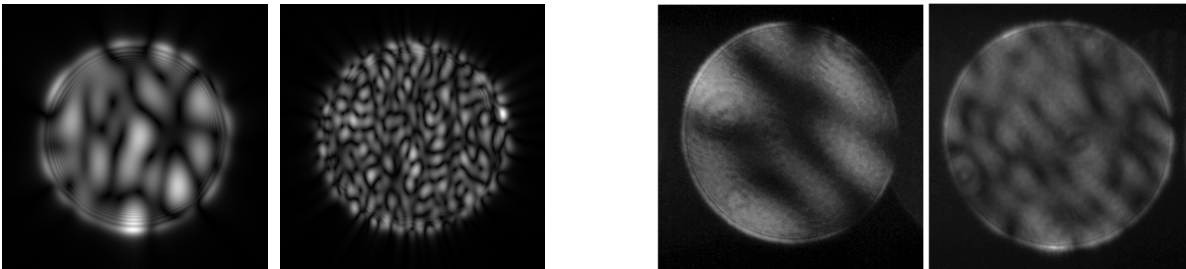


Figure 5 Speckle structure of small and large rough particles. Left: Simulation, Right: Measurement

2.3 Optimization for high particle concentration and continuous measurements

In real technical and natural processes, however, the number of particles is usually so large that the defocused images overlap heavily and can no longer be analyzed. Examples are environmental water applications or flows in cavitation processes, e.g., propeller inflow. Generally, the inflow contains a large number of solid particles and only a few bubbles. For cavitation prediction the

microbubbles induce cavitation. The Hydrodynamic Nuclei Concentration Technique (HDNC) was developed for this application (Ebert 2015). A laser beam illuminates a one-dimensional measurement line-like volume. The flow perpendicular to the laser beam is scanned for particles (see Figure 2). The advantage of the line-like illumination is that the defocused images can also be separated for high particle concentrations. The frame rate can be up to several thousand frames per second (fps), as only one image strip is used (see Figure 6).

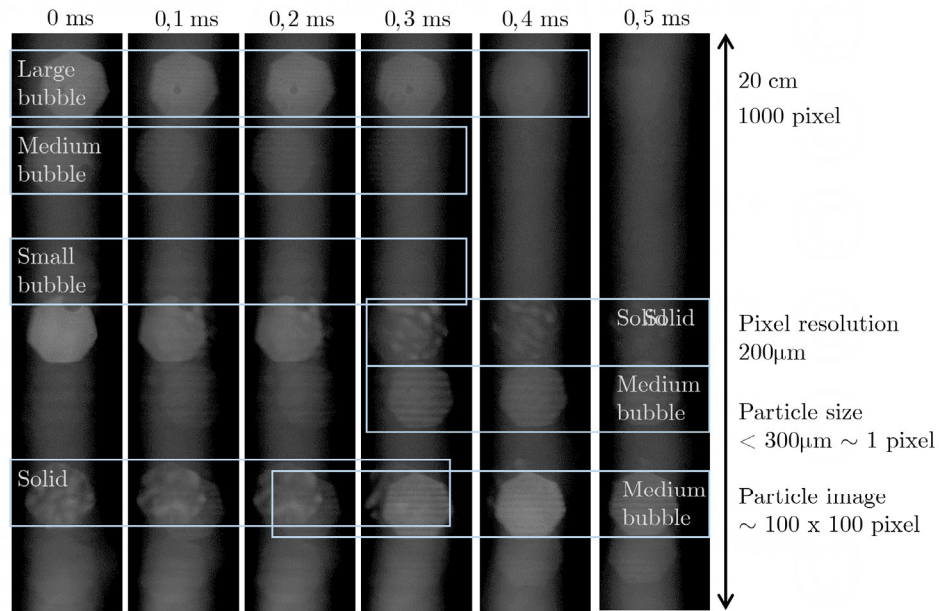


Figure 6 Example sequence of an HDNC measurement with 6 images at 10 000fps and a measurement time of 500μs detecting bubbles and rough solid particles

With HDNC technique, a large fluid volume can be analyzed in a short time (e.g., 0.001 m³/s) with large number of particles (e.g., 6000 particles/s). The reason for this is that HDNC technology allows the observation field and pixel resolution to be decoupled from each other, e.g., 20 cm measuring volume length and resolution of 10μm particle size can be realized with about 2000 pixels.

For even higher particle concentrations, the defocused images also overlap. The spherical apertures used produce circular defocused images and make it difficult to detect, separate, and analyze the particles. Simultaneously, the computing effort increases for detection of circles (Figure 7).

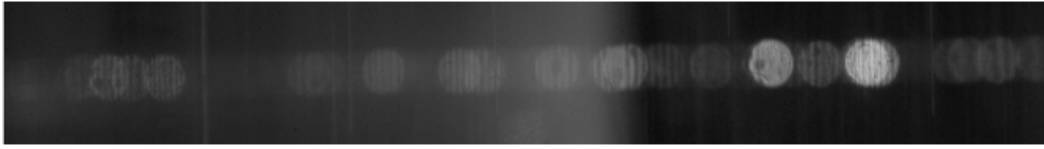


Figure 7 Example of HDNC image with high particle concentration and image overlap.

By adjusting the aperture shape, similar to Steinmetz et al. (2025), improved signal conditioning can be achieved for evaluation. A square aperture shape was favored. Very robust single particle detection (see Figure 8) can then be achieved by means of simple line summation (blue line) and correlation of a rectangular function (red lines). At the same time, images of individual particles can be reliably separated (see Figure 8) and also overlapping particles can be counted for extrapolating the particle statistic.

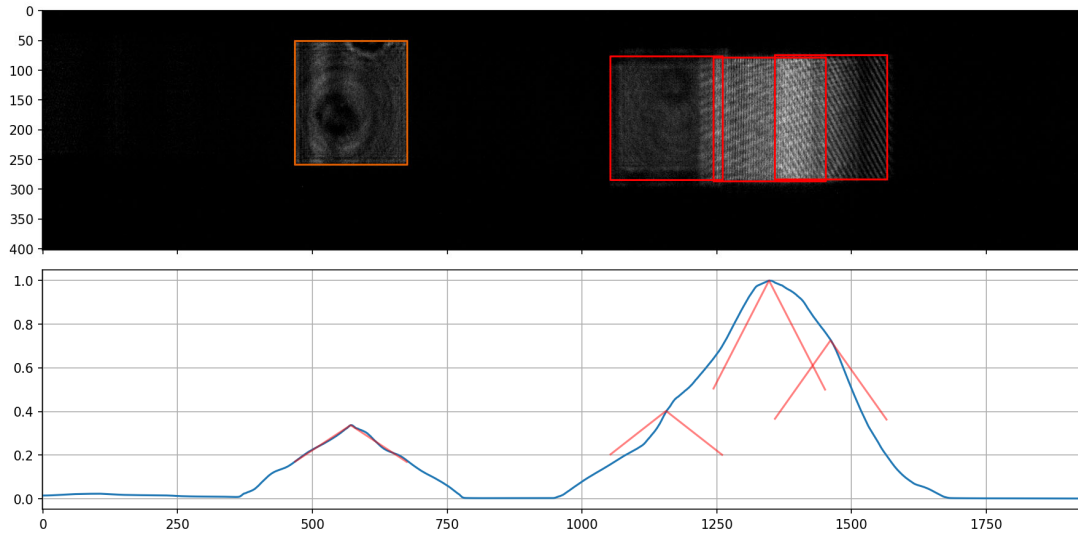


Figure 8 Particle detection for square apertures (organs: single particle, red superimposed particle images). Bottom: Correlation between line sum signal and rectangular filter (blue) and single particle model (red)

The particle size statistics for the individual particle types are estimated from the reliably detected single particle signals (orange in the Figure 8). For spherical particles, a simple addition of the Fourier transform values of the rows is sufficient. For non-spherical particles, the maximum size is determined based on the speckle structures. Here, too, the square shape of the aperture offers advantages in terms of computing time and complexity. A decisive advantage is that the algorithm used can be transferred to the available smart camera system, enabling real-time capability and continuous measurements in the future.

The detection volumes of the individual particle classes are then estimated using the intensity statistics within the reliably detected single particle images. The detection volume for small particles is smaller than the detection volume for large particles. The concentration of small particles is underestimated. At the same time, the intensities for each particle class are limited to a maximum value. The detection volume size can be statistically estimated from the intensity statistics for each particle class (similar to Albrecht et al. 2003, ch 12). The assumption here is that the scattered light conduction increases quadratically with the particle diameter. An example of the statistics is shown in Figure 9.

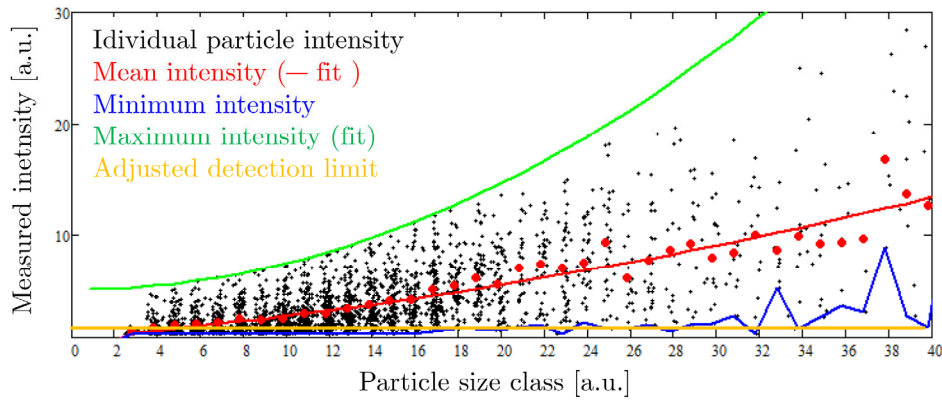


Figure 9 Intensity dependence of defocused images on particle size

By setting a detection threshold (orange in the Figure 9), the detection area can be estimated when the particles pass through, together with the size information and the Gaussian intensity distribution of the laser beam. This detection area is then used to correct the size statistics. This allows a lower detectable threshold to be set. Furthermore, concentrations and flows of particle types and classes are derived from this.

3 Example Measurement Application

As an experimental example, measurements taken at the cavitation tunnel at the University of Rostock (Ebert et al. 2017) were again analyzed with regard to particle classification, concentration determination, and particle size determination. The cavitation tunnel K21 measures $5.8\text{m} \times 1.5\text{m} \times 3.4\text{m}$ and has a centerline length of 13.38 m. A bubble injection system was installed in the measurement section of the cavitation tunnel (see Figure 10), and the water was temporarily seeded with bubbles.

Several measurement positions were examined. The following example analysis refers to measurement position 1 (laser position 1 Figure 10), located upstream of the bubble injector.

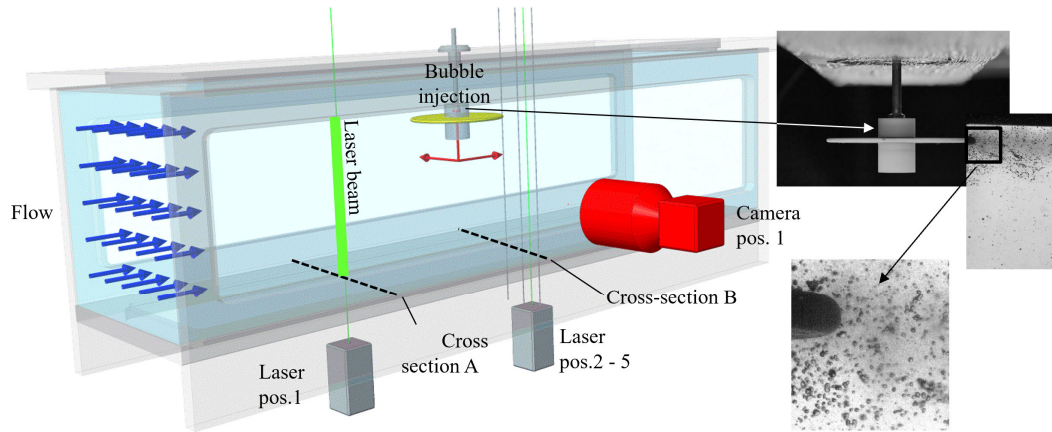


Figure 10 Test setup for bubble measurements in a cavitation tunnel. Left: Schematic illustration, Right: Bubble injection system

The measurement clearly illustrates the dynamics of the cavitation tunnel in terms of bubble concentration (Figure 11).

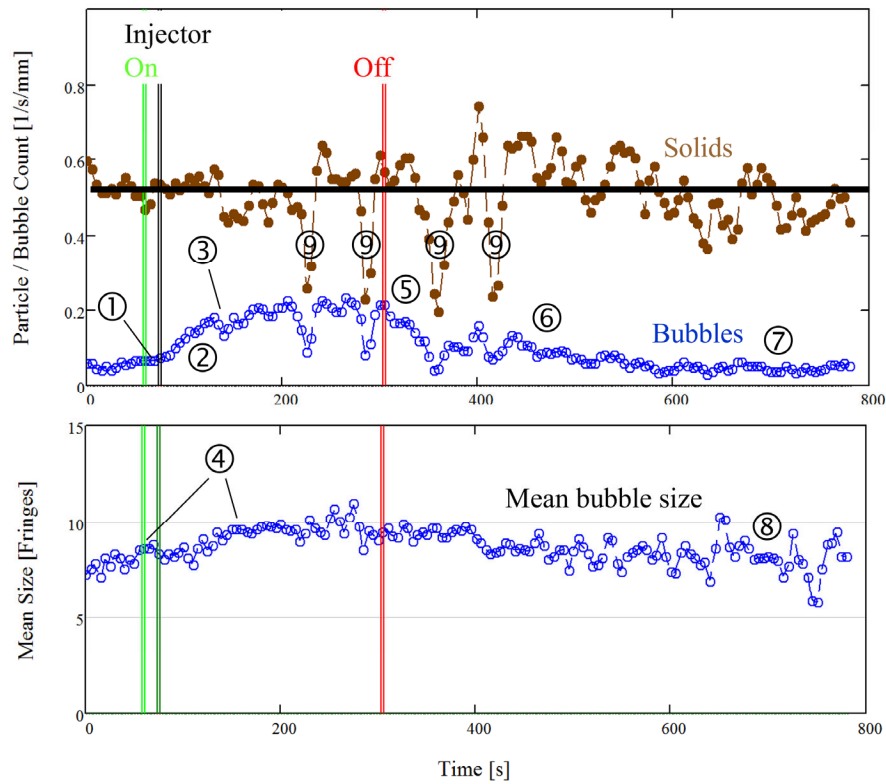


Figure 11 Time-dependent bubble and solid particle concentrations during bubble injection in a cavitation tunnel

The upper diagram in Figure 11 shows the particle flux per second and per unit length along the laser beam. The brown curve represents the flux of non-spherical particles (solid phase). The blue curve shows the flux of bubbles (gaseous phase). The bubble injector was turned on at the time marked with green line and turned off at the time marked in red.

After the injector is turned on, the generated bubbles must first flow through the entire cavitation tunnel, since the measurement is taken upstream of the injector. A dead time of approximately 12 seconds can be observed between the moment the injector is turned on and the rise in bubble concentration (1). This is consistent with the tunnel's circulation time, which was 10 seconds.

Thereafter, the bubble concentration increases continuously (2) and reaches a steady-state region (3) with a time constant of approximately 40 seconds (4 cycles). In contrast, the concentration of solid particles (brown curve) remains nearly constant even after startup and throughout the entire measurement. The increase in bubble concentration is coupled with an increase in the mean diameter of approximately 25% (4), since the generated bubbles have not yet dissolved in the water.

After the injector is turned off (red line), the bubble concentration (5) decreases. However, the time constant is significantly larger than during the startup process of injection (6) and is approximately 200 seconds (20 cycles). The bubbles slowly dissolve in the water, causing both the concentration (6) and the average diameter to decrease. Only after approximately 300 to 400 seconds (30 to 40 cycles) do the bubble concentration (7) and average bubble size present at the start of the experiment return to their original levels (8).

During the measurements, fluctuations in both solid concentration and bubble concentration can be observed (9). This is due to the bubbles slowly moving within the boundary layer at the optical window during the measurements, thereby disturbing the laser illumination and disrupting the measurement.

The time constants must be taken into account for cavitation experiments in cavitation tunnels with circulation. Otherwise, the cavitation behavior cannot be compared across different operating points. For large tunnels, the larger time constants of about 15 to 30 minutes must be considered for valid measurements between cavitation experiments, especially when cavitation itself generates bubbles.

4 Perspective

The objective is to apply the technology also to the detection of microplastic particles. Based on current knowledge, it is not possible to separate microplastic particles from organic and inorganic solids using the interference pattern. Additional spectroscopic information is required for this purpose. The approach to material determination is described in Merck (2025) and is not covered in this article due to its scope. However, the environmental impact of microplastic particles can only be estimated by estimating their concentration, effective surface area (e.g., Sauter mean diameter) and size distribution. Therefore, both methods, spectroscopy and particle counting, must be combined for a realistic measurement. Because of the low concentration of microplastic particles a large volume must be tested and requires continues measuring techniques with high flux.

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