High-speed x-ray CT imaging of a strongly cavitating nozzle flow

D Bauer ©, F Barthel and U Hampel
Helmholtz-Zentrum Dresden-Rossendorf e.V. Bautzner Landstrasse 400, 01328 Dresden, Germany
E-mail: daniel.bauer@hzdr.de and d-bauer@gmx.net
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Abstract
Examining or imaging of internal structures in flows with cavitation is still one of the greatest challenges in this field of research. In a specially designed nozzle, a strong cavitation region (CR) is generated with a liquid core (LC) in the center, surrounded by vapour. While it is almost not feasible to visualize the inside of the CR with visible light, it is shown that with high-speed x-ray computed tomography it is possible to visualize the dynamics of the unsteady cavitational flow structures inside the CR. The observed phenomena start with a ring of cavitation and small amounts of vapour inside the LC at / near the entrance of the cavitation channel. Further downstream the cavitation is growing rapidly and cavitation structures inside the LC can be identified. In addition the results are compared with former time averaged CT images of the same nozzle and with results obtained from high-speed videography.

1. Introduction
Cavitation is the occurrence of vapor cavities at very low static pressure in fast liquid flows, playing an important role in different engineering applications such as fuel injection nozzles [1–3], ship propellers [4] and hydraulic systems [5]. In the first example, cavitation can cause instabilities and flow rate fluctuations that lead to improved vaporization of the fuel. Although numerical investigations of flows with cavitation have become more and more sophisticated within the past two decades [6, 7], there is still a need for carefully designed experiments, for example, for model development and validation.

Typical visualisation techniques to observe cavitation structures are photographic images or videography. This is usually done with glass or acrylic glass models to guarantee optical access. Mock-ups exist for large [8] and small scales [1, 3, 9]. Image acquisition is usually performed with high-speed or double shutter CCD cameras [1, 10, 11]. By post-processing the images, quantitative and qualitative data, such as e.g. the amount of gas bubbles inside the liquid can be derived from the pictures [5]. But, this is only achievable for moderate cavitation. If the cavitation is stronger, large cavitation regions inside the fluid can hide the view on smaller structures, causing errors in the quantitative or even in the qualitative analysis.

To investigate 3D cavitation structures inside a fuel injection nozzle, Chaves et al [3] have used a transparent real size VCO® nozzle with a transparent needle. Thus, it was possible to take images from the direction of the hole’s exit. With this experimental set-up, Chaves et al have described the so called pig tail cavitation which demonstrates the 3D nature of the cavitation inside an injection nozzle.

However, even with such a highly sophisticated experimental technique, it renders it very difficult to measure cavitation structures or the actual void fraction in flows with cavitation. Hence, in recent years, radiological methods have become increasingly common to investigate multiphase flows such as flows with cavitation in nozzles [2, 12–14], pipes [15], pumps [16] and obstacles [17–20]. The reason for choosing these techniques lays in the fact, that with radiation of higher energy, scattering effects at the phase boundary between the liquid and the gas can be neglected. The dimensions of the regions of interest (ROI) in the experiments vary from a few 100 micrometers up to several centimetres.

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Attempts in the early history to investigate flows with cavitation using tube source x-rays have been presented by Stutz et al (2003) [21] and Coutier-Delgosha et al (2006) [22]. These groups have measured the vapour volume fraction of sheet cavitation over a hydrofoil inside a two-dimensional channel flow. With their x-ray attenuation device, which consists of an x-ray tube source and 24 detectors, they were able to measure the volume fraction of the vapour phase with a frequency up to 1000 Hz. In addition they have compared the results with pressure measurements and endoscopic imaging with good agreement.

A similar approach in cavitation research has been presented by Ganesh et al [17, 18]. They have used a special imaging sub system which converts the incoming x-ray radiation into visible light in order to record high-speed x-ray images with a conventional scientific high-speed camera, directly. Details about the system can be found in [20].

Within the last decade, x-ray flow diagnostics or imaging became also popular to investigate the injection process of fuel injection systems. Liu et al and Wang et al, for example, characterized the dense spray of fuel injection nozzles (external flow) [23] with fast x-ray velocimetry and x-ray tomography. Other research groups put the focus on the cavitation of the internal flow of injection nozzles and performed x-ray or time averaged x-ray CT measurements in real size nozzles.

Duke et al and Battistoni et al investigated the influence of dissolved gas in cavitation in a real size Diesel-injection-nozzle [2, 12, 13]. It has been known before [4] that dissolved gases serve as cavitation nuclei. In a very sophisticated experiment, Duke et al doped the liquid phase of deionized water with a bromine tracer. Afterwards, krypton, which serves as a replacement for the removed air, was dissolved in the deionized water, representing the solved gaseous phase. Due to the illumination with a single, monochromatic x-ray beam from a synchrotron source (focus-spot 5 × 6 μm), the fluorescence agents bromine and krypton emitted x-rays at a specific wave length. With a photon-counting silicon drift diode detector, the incoming radiation can be examined and the group was able to distinguish which substance contributes to the void fraction inside the nozzle. By scanning the nozzle ‘point by point’, the researchers obtain a statistically averaged, integral void fraction distribution of the whole nozzle and they could also see how much each substance contributes to the void at a certain position inside the nozzle. By rotating the nozzle relative to the beam, the group showed that it is possible to derive a full three-dimensional, time averaged concentration measurement of the phase fractions with this technique.

These so far mentioned, very sophisticated studies of internal nozzle flow, either provide an integral image of the attenuation of the x-rays or a time averaged image of the void-fraction distribution. This fact has promoted the idea to investigate cavitation flows with x-ray computed tomography (CT) to resolve the 3D structure of the cavitation. The advantage of x-ray CT imaging is that one obtains slices of the void fraction distribution inside the cavitation region (CR). These images can then be used for qualitative or quantitative analysis of the observed cavitation structures within the flow.

To the best of our knowledge, the first attempt to investigate an internal cavitation flow with a x-ray CT-scanner was published in 2012. Bauer et al [15] have used a standard medical CT-scanner to investigate cavitation inside a purpose built nozzle with which it was possible to create a stable and quasi steady cavitation area inside. At high flow rate, the liquid inside the cavitation channel separates completely from the wall (film cavitation). With the CT imaging technique it was possible to visualise a new cavitation area inside the separated liquid flow. Although this technique provided a new point of view on flows with cavitation, there is a major drawback of the technique presented in [15]. Flows with cavitation are usually very fast and the frame rate of the used medical CT system was very low (max. 2 slices per second). As a consequence, this only leads to strongly time averaged images of the cavitation.

An x-ray CT imaging technique has also successfully been used in smaller scale with a purpose-built single hole nozzle (D = 3 mm, L = 9.5 mm) by Mitroglou et al [14]. This nozzle was installed in a compact high pressure test-rig. The group has used a prototype micro CT at the University of Bergamo (Italy) to perform CT measurements of the cavitation flow inside the nozzle. The CT device consists of a 160 kV @ 400 μA cone x-ray source, an air-bearing direct drive rotary stage and a 1944 × 1536 pixels flat panel CMOS detector [14, 24]. The achieved voxel size for the measurements was 15x15x15 μm³. In their experiments they kept the needle position fix and run the set-up under continuous flow condition. The temperature was kept constant at 40(±0.5) °C. For the measurements the whole high pressure test-rig was placed on the rotary stage of the CT system and the nozzle was scanned with 600 projections for a full revolution (0.6° steps). The measurement time for a complete 3D data set of one test condition was with approximately 1h very long. Although the results from the CT images were only averaged over a very long period of time, they show the possibility to perform x-ray CT imaging of cavitation flows in small nozzle sizes. With additional high speed shadowgraphy of the flow, the group was able to derive valuable statistical information about the transient features of the flow field [14].

These so far mentioned examples reveal that imaging or measuring cavitation with x-ray techniques can either be fast, by only delivering an integral image of the void fraction, or time averaged in a 3D voxel space. To close at least one of these gaps, the authors have investigated the internal flow of the nozzle, that was used by
Bauer et al 2012 [15], with high-speed x-ray CT. Although the nozzle was designed to create quasi steady cavitation, the herein investigated flow is highly turbulent and highly dynamic to show the potential of using high-speed x-ray CT in flows with occurring cavitation. With the system, frame rates of 1000 slices per second were utilized with voxel sizes of 1 mm³.

This technique has previously successfully been used for investigation of multiphase flow dynamics in various applications. In 2017, a comprehensive study of air/water and steam/water pipe flow in the vertical test section of Thermal Hydraulic Test Facility TOPFLOW was done [25]. Janzen et al used this technique for studies of dynamic liquid distribution and hold-up in structured packages [26, 27]. Schubert et al disclosed the flow structure in monolithic ceramics [28].

The results from the high-speed CT imaging, presented in this work, are compared with former averaged CT measurements [15] of the same nozzle and findings of other groups published in current literature. In addition high speed videography was used for further interpretation of the results.

2. Measurement instrumentation

Within the next few paragraphs, the measurement instrumentation used for the presented investigation is introduced.

2.1. Ultrafast x-ray CT scanner

The ultrafast x-ray CT (ROFEX) utilizes a free electron beam, which is formed and deflected by means of electron optics to generate a moving x-ray source. The focal spot is guided on a semi-circular target around the object of investigation. The x-rays emitted from the focal spot pass the object and are thereby attenuated due to electron optics to generate a moving x-ray source. The focal spot is guided on a semi-circular target around the object. It reaches 1 mm within the image plane and a plane thickness of 1 mm, at best conditions. The ROFEX scanner comprises two imaging planes with 2 independent detector rings, which can be addressed alternatively. Thus, sequences of slice image pairs can be produced, with an axial distance of 13 mm. From these data, the scanner gives access to information of the interfacial area of the object. It reaches 1 mm within the image plane and a plane thickness of 1 mm, at best conditions. The ROFEX scanner comprises two imaging planes with 2 independent detector rings, which can be addressed alternatively. Thus, sequences of slice image pairs can be produced, with an axial distance of 13 mm. From these data, the information of the interfacial area of the flow structure can be derived. For further details see [29] and [30].

The ROFEX scanner has been used for relatively slow multiphase flows, so far. In case of cavitation, the velocity of the fluid is very high. That means that a structure within the measurement plane only contributes completely to the reconstruction of the image if it is present in the plane for one revolution of the x-ray beam. With the velocity of the fluid $u_{fluid}$ and the time of one x-ray beam revolution $t_{rev}$, a minimal length of the structures ($LS_{min}$) can be calculated for which they fully contribute to the reconstruction process, which is

$$LS_{min} = u_{fluid} \cdot t_{rev}$$

(1)

This equation is based on the assumption, that at the start of one revolution of the focal spot, the structure just entered the measurement plane. If in addition the void fraction within the structure is almost constant and the cross-sectional shape of the structure is not changing too much, the structure can be imaged without significant artefacts. But it has to be mentioned that due to the high dynamics of the flow, motion artefacts are present if the position and strength of the cavitation change strongly within one revolution of the electron beam. Due to motion artefacts the reconstructed image appears blurry and attenuation coefficients throughout the whole reconstruction area might not be reconstructed exactly. These errors are very well visible in the reconstructed areas of the shell of the nozzle where the attenuation coefficient of the acrylic glass appears not homogeneous in the reconstructed images.

Because the dwell time of cavitation structures within the measurement plane and motion artefacts, exact measurements of the water or void fractions are hardly possible and the results have to be considered as time averaged (within one revolution cycle), in a qualitative way. Further on, the resulting image must not be considered as time resolved but can be judged as time averaged within a short time interval. Thus, the ROFEX scanner gives access to flow morphology in the sub-millisecond time scale for the first time and must be understood as a next step of evolution in highly sophisticated flow imaging techniques for flows with cavitation.

2.2. Pressure measurements

Within the present study, we have measured the static pressure before ($p_1$) and after ($p_2$) the cavitation channel in order to calculate the cavitation number $C_n$ [1], which is defined as
where \( p_V \) is the vapour pressure of water. Since \( p_V \ll p_2 \), equation (2) can be well approximated as

\[
C_n = \frac{p_1 - p_2}{p_2}.
\]

The pressure was measured via pressure tappings and small, flexible tubes with an inner diameter of 1 mm. From each measurement position, the small pipes end in a hydraulic switch. The pressure gauge is connected to one connection of the switch. The tubes were filled with water and care was taken to eliminate enclosed air from the system. Each connection can be opened and closed by a ball valve. Thereby, the static pressure at each measurement position can be obtained independently.

The employed pressure gauge was an analogue manometer. With this instrument, values of the absolute pressure in range of 0–4000 mbar can be measured with a read-off accuracy of 50 mbar. The cavitation number can therefore be calculated with a maximal error of 9%.

2.3. High-speed videography

For the high-speed images a Photron APX-RS high-speed camera, equipped with a Nikor 35 mm F1.4 lens, was used to take high-speed video images of the cavitation. With this camera it is possible to take images at 3000 fps at 1024 \( \times \) 1024 pixels. In our experiment we have used a rectangular image section with 256 \( \times \) 912 pixels whereby a maximum frame rate of 9000 fps was possible. For the illumination, a 1000 W halogen lamp was used to illuminate the nozzle. In order to prevent strong reflections at the round surface of the nozzle, the lamp was placed at an angle of 90° to the camera. Important for the image quality are very short exposure times. In our case, the exposure time was set to 1/40000 s in order to prevent motion blur of the images.
The camera is equipped with 6 Gb RAM through which it was possible to take 9200 images at the above mentioned resolution. This corresponds to a recording time of 1 s.

3. Experimental set-up

The nozzle in which cavitation was generated is shown in figure 1. The same nozzle has been used by the first author to perform time averaged void fraction measurements with a medical CT-systen [15]. In the present paper the authors will focus on a highly cavitating case to show the potential of the high-speed CT system applied on this kind of flows.
The basic idea to generate quasi steady cavitation is illustrated in the nozzle cross-section in figure 2. Water flows from the pipe into the nozzle inlet and is guided through three slits towards the outside between an acrylic glass cylinder and the outer shell of the nozzle. The cylinder has no sharp edges at the end in order to avoid separation at this point. The flow is then guided towards the direction of the cavitation channel.

The distance \( Z^* \) between the front of the cylinder and the entrance to the cavitation channel (20 mm in diameter, 100 mm in length) can be adjusted. The closer the cylinder is to the cavitation channel the higher is the entrance velocity. This, in addition to the abrupt 90° flow turn causes a very low static pressure at the entrance of the channel, resulting in cavitation. In a previous publication [15], it has been shown that with this nozzle it is possible to generate different types of cavitation, starting with light, cloud-like, cavitation up to film cavitation, at which the liquid flow is separated completely from the wall by vapour. In the present study, only cases with strong cavitation are of interest and therefore the distance between the cylinder and the cavitation channel was set to \( Z^* = 2 \) mm.

After the cavitation channel, the diameter of the nozzle increases to 70 mm in order to raise the pressure and cause the collapse of cavitation. Special care was taken to ensure that no metal parts were within the x-ray beam to avoid artefacts. The perfect shell around the cavitation channel is important, in order to prevent artefacts in the CT images and optical disturbances in the photographs. The junctions for the gauge meter were realized with small and flexible plastic pipes, which were glued in the shell of the nozzle.

The nozzle has been integrated into a simple flow test rig (figure 3).

The maximum flow rate \( \dot{V} \) depends on the distance \( Z^* \). For the present study, the flow rate was set to \( \dot{V} = 4.0 \text{l s}^{-1} \) for \( Z^* = 2 \) mm. For that case the velocity inside the cavitation channel is 12.7 ms\(^{-1} \) which corresponds to a Reynolds number of \( Re = 2.53 \cdot 10^5 \) and a Cavitation number of \( C_n = 2.4 (p_1 = 2.7 \text{ bar, } p_2 = 0.8 \text{ bar}) \). The residence time of the fluid inside the cavitation channel at this velocity is nominally \( t_r = 7.9 \text{ ms} \). Thus, the minimum length of a structure, to contribute fully to the image-reconstruction, is \( L S_{\text{min}} = 12.7 \text{ mm} \), at best case (see equation (1) in section 2.1). At these flow parameters, strong film cavitation at a high level of turbulence can be expected (see Bauer 2012 [15]). The diameters of the pipes are 3.2 cm at the suction and pressure side of the pump and 5.1 cm between exit of the nozzle and the tank. A flow meter was integrated in flow circuit to measure the flow rate and a heat exchanger was installed into the tank to keep the temperature constant at 20 °C.

In figure 4 the installed nozzle and the measurement set-up at the ROFEX scanner can be seen.

4. CT calibration

The aim of the calibration procedure is the conversion of the pixel values, which represent the attenuation of the object at this specific location, into a value that represents the amount of liquid water at this point. The ROFEX CT only gives relative attenuation values in the image, depending on the attenuation present in reference data. Thus, reconstructed gray value images have to be scaled on gray or coloured values for gas and liquid phase, respectively. It has to be mentioned, that the reconstructed images from the CT are stored in tif—format and the pixel value (PV) is stored in floating point numbers with 32 bit resolution and the values for liquid and gas have to be obtained in the calibration. Thus, 2 image series of 1000 images were recorded, one for air and one for
liquid water, without any flow. These series were temporally averaged (see figure 5). It can be seen in the image of air (figure 5(a)), that the border of the channel (depicted as dashed circles in figure 5) does not appear as a sharp edge. A transition of the pixel value from black over red to yellow is visible (in the image for air). This phenomenon has its reason in the reconstruction algorithm of the CT-system. From each averaged image the averaged pixel value inside the channel was calculated, such that the pixel values within a diameter of 16 mm around the center were averaged (region depicted as solid circles in figure 5), too. Because of the smaller diameter, compared to the diameter of the hole, the transition of the PV from the media within the channel to the acrylic glass was left out from the calculation of the averaged value. With the smaller diameter for the calculation, only pixel values which represent the pixel value of the media inside the channel, were used for the calculation of averaged pixel value of the media inside the channel. The results are $PV_{\text{air}} = 0.48$ and $PV_{\text{fluid}} = 0.56$. The black areas at the corners within the images are due to the post processing algorithm and have no physical meaning.

For the dynamic measurements the assumption was made that the gray value changes linearly with the amount of the gaseous phase located within a certain voxel position. If the pixel values of water ($PV_{\text{fluid}}$) and air ($PV_{\text{air}}$) are known, a value $\alpha$ can be defined that represents the relative amount of liquid water within one voxel. $\alpha$ is then given by

\[
\alpha = \frac{(PV_{\text{cav}} - PV_{\text{air}})}{(PV_{\text{fluid}} - PV_{\text{air}})} \cdot 100\%.
\]  

In equation (4) $PV_{\text{cav}}$ represents the pixel value of the mixture of water and the gaseous phase (cavitation).

From the calibration images, another, device specific issue is visible in the calibration image for air (figure 5(a)). At the right of the image a slightly lower attenuation for the material of the nozzle was measured. This effect is due to a limited angle artefact, which is caused by the ROFEX. The target ring of the scanner is not fully closed but has an opening on one side. Thus, the projection angle is 240°. If the object of investigation is mounted near the opening, which was done in the presented study for space reasons, a limited angle artefact can occur and the attenuation is not reconstructed exactly in the direction of the opening of the target. For the interpretation of the CT images, this has to be taken into account. Further details on limited angle artefacts of the ROFEX can be found in Bieberle 2006 [31].

5. Results

In this paragraph the experimental findings from the ROFEX measurements are presented. In figure 6 an overview of the flow inside the cavitation channel with strong cavitation at 12.7 ms$^{-1}$ is shown. Just from the entrance of the cavitation channel, cavitation starts at the sharp inlet of channel and the water flow separates completely from the wall, forming a liquid core, completely enveloped by vapour. Unfortunately, the entrance to the channel and start of the cavitation at sharp edges of the entrance is not visible in the photograph because of a slightly tilted viewing angle of the camera, in order to fully capture more interesting parts of the flow. From figure 6 it can be seen that within the first quarter of the channel (figure 6(I)) the cavitation on the surface of the liquid core (LC) flow is moderate with only tiny bubbles and disturbances. Further downstream the interactions of the LC and the gas filled area between the LC and the nozzle wall becomes stronger disturbed and unsteady, the shape of the flow reveals strong turbulence and larger bubbles are visible in this area (figure 6(II)). Due to the larger bubbles, the light is more scattered through which the image appears brighter in this area than at the entrance of the channel. This region occupies approximately half of the length of the channel. Close to the end, about the distance of one diameter, the appearance of the flow changes rapidly from bubble cavitation to cloud-
like cavitation and most of the area is filled with liquid water, indicating the final collapse of the cavitation (figure 6). The higher brightness of the image in this area is because of light reflections at the surface of cavitation bubbles or clouds. It has to be mentioned, that the positions of the three zones are not fixed, but vary along the channel during the measurements.

5.1. Averaged void fraction
The aim of this section is to present the results of time averaged high-speed CT images. The images were time-averaged over 1 s, which means that 1000 single images contribute to the resulting averaged image. As
mentioned before in section 4, the black color in the corners of the images is due to the post-processing algorithm and has therefore no physical meaning. The axial measurement positions of the CT are marked within the photographs at the bottom of each figure.

The image set from which the first presented figure (figure 7) was derived, has been measured at $z = 3 \text{ mm}$ after the entrance of the cavitation channel. The measurement position is marked with a white line in the photograph of figure 7. As mentioned in the previous section, the entrance to the channel and the start of the cavitation at sharp edges of the entrance are not clearly visible in the photograph of figure 7 because of a slightly tilted viewing angle of the camera.

Figure 9. Averaged ROFEX image at $z = 57 \text{ mm}$; white line in the photograph indicates the measurement position.

Figure 10. Averaged ROFEX image at $z = 92 \text{ mm}$; white line in the photograph indicates the measurement position.
In the CT image, a dark ring of strong cavitation is visible which separates the liquid (bright colour around the center) completely from the wall. Within the ring there is no liquid water visible. Equivalent results have been found at this measurement position, by investigating the same nozzle with a medical CT [15].

In addition, an asymmetry of the cavitation ring can be seen. In the image, the asymmetry appears as higher values of \( \alpha \) (higher amount of liquid water) on the right of the CT image of figure 7 whereby the thickness of the ring of strong cavitation (black color) seems to be thinner as in the rest of the image. The phenomenon of brighter pixel values on the right of the CT image was also visible in the calibration images (see figure 5) and is caused by artefacts. For the further interpretation of the CT images it has to be taken into account that on the right of the images a higher amount of liquid is displayed, which is not the reason of less cavitation in this area.

The image in figure 8 was calculated based on an image set, which was taken at \( z = 33 \) mm behind the entrance of the cavitation channel. Half of the cavitation ring is still visible but is not as pronounced as in figure 7. This is a sign that during the time, in which this image set was taken, a larger quantity of liquid has been within the near wall area. Inside the liquid core, a large cavitation zone is visible (darker color). However, a large connected area, which contains mainly liquid water is visible, too. Similar results of a cavitation zone inside the liquid core have also been found in the measurements with a medical CT [15]. The fact that the zone of stronger cavitation is not directly in the middle, but occupies over the half of the cross-section of the LC, might be a reason of a different fluid-dynamical set-up of the nozzle compared to the set-up published in Bauer 2012 [15]. Due to the mounting of the nozzle within the ROFEX, in the presented study, there was a tight curvature of the inlet pipe. Due to this curvature, the flow at the inlet of the nozzle is not perfectly symmetric and areas of higher velocity cause lower pressure and therefore show stronger cavitation. From this result it is obvious that the scanner is able to capture phenomena which have their origin in the upstream flow configuration. This can e.g. be of interest if cavitation within hydraulic parts, like valves, should be investigated.

The next picture in this section (figure 9) shows an averaged image in the middle of the channel, at \( z = 57 \) mm. The whole channel is filled with vapour and parts of a cavitation ring are still visible on the left. This result is similar to the result of the medical CT scanner with cavitation at similar strength.

The last picture in this section (figure 10) shows an image of the averaged amount of liquid water \( \alpha \) in the collapse region of the cavitation channel (zone III in figure 6). It is clearly visible from figure 10 that the value of \( \alpha \) is close to 100% of liquid water but the slightly darker values indicate that some void is still present in this region of the cavitation channel.

The results of the averaged images are in good agreement with previous CT results obtained with a medical CT scanner (see Bauer 2012 [15]) and both systems are able to image the averaged water or void fraction in flows with cavitation.

### 5.2. Results of high-speed CT imaging

In this section the capability of capturing dynamic events in flows with cavitation by the ROFEX will be discussed. As mentioned earlier, the velocity of the investigated flow is with 12.7 m s\(^{-1}\) very high and the obtained images are reconstructed from projections of a measurement duration of 1 ms. In figure 11 a sequence of 8 CT images, taken at \( z = 33 \) mm with a time interval of \( \Delta t = 1 \) ms between the images is depicted. The occurrence of cavitation is clearly to be seen. Because the time resolution of the scans (i.e. 1 ms) is too slow for the mean liquid velocity of 12.7 m/s, pixel values in the images gives probabilities of gas fraction for each pixel. Nonetheless, snapshots of single vacue and the evolution of cavitation structures can be accessed by the ROFEX. The cavitation ring is visible very well and the fast appearing and vanishing cavitation structures in the LC demonstrate the dynamic and unsteady structure of the flow, which will now be discussed for several positions in the cavitation channel.

![Figure 11. Slice image sequences, taken from dataset \( z = 33 \) mm. Colours represent \( \alpha \).](image-url)
In figure 12 two CT images at the entrance of the cavitation channel are depicted. Each image represents the reconstructed CT image in one of the two measurement planes of the ROFEX. The z-position of the 1st plane (figure 12(a)) was \( z = 3 \) mm downstream from the entrance of the cavitation channel. The image of the second plane, which is located 13 mm further downstream, is displayed in figure 12(b). Both images were taken out of a set of 1000 images and were recorded one after the other with a time interval of \( \Delta t = 0.5 \) ms. Note here, that very short data acquisition time for each projection results in a low SNR, which leads to noisy images. Within both images, the cavitation ring at the wall of the channel is clearly visible (dark color) and the center is occupied mostly by liquid water.

One thing that is directly visible within the images, is that \( \alpha \) within the ring does not decrease to 0% of liquid water at the right of figure 12(b) (dashed box), which was already discussed in section 5. Another thing, which clearly stands out, is that due to the highly dynamic flow, cavitation structures change within one projection cycle and areas of cavitation do sometimes not fully contribute to all projections employed for the reconstruction. The appearance and vanishing of these structures within one revolution of the x-ray source cause motion artefacts. Thus the noise level of the images rises. This has a direct impact on the quantitative analysis of the images.

But even at such a high level of noise and the fact, that the images are quasi time averaged, the developing cavitation can be visualised. It is clearly visible, that the void fraction in the LC and the ring rises from figure 12(a) to figure 12(b) (darker colour in the LC and thicker ring).

In figure 13 cavitation structures imaged at the end of the 1st third of the cavitation channel are presented. The cavitation ring at the wall is still present, whereby its void fraction is less pronounced, compared to figure 12. In the wall region, a large cavitation area is visible (dotted rectangle). It can clearly be seen that the size of the structure is slightly growing from figures 13(a) to 13(b) but its shape is overall preserved. However, the most interesting structure is marked with the black arrows. The dark color of the structure is an indication for two interesting facts. First, the structure was present within the measurement plane for the time of one full revolution of the electron beam and therefore contributes fully to the calculation of the attenuation values. Second, no liquid water can be found within the structure. That means that the minimal length of the structure can be calculated with equation (1), which leads to minimal structure length of \( L_{S_{\text{min}}} = 12.7 \) mm. Unlike the cavitation region at the wall, the dimension of the dark spot is not growing from figures 13(a) to 13(b). Furthermore, this small and dark spot is visible in both planes, approximately at the same position. These facts lead to the conclusion that the two spots belong to the same structure. It can further be seen in the image that the structure has no direct connection to the wall region but develops most likely from cavitation nuclei within the wall.

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**Figure 12.** CT image at the entrance of the channel; (a) 1st plane, (b) 2nd plane; position of the first plane \( z = 3 \) mm, plane distance 13 mm, \( \Delta t = 0.5 \) ms; pseudocolours indicate amount of liquid water, \( \alpha \); dotted box ...higher amount of liquid water; photograph shows location of measurement planes.
liquid core. From the images, the structure can be interpreted as elongated bubble, completely filled with vapour. To the knowledge of the author, this is the first time that an independent structure of strong cavitation was imaged inside a strong cavitation region.

From the points just mentioned, the dark spots could also show a cavitation string vortex. This form of cavitation is well known in the field of cavitation research [6, 8–10]. Unfortunately, the velocity has not been analysed and the vortex flow could not be identified, so far. This will be part of future research and further post-processing of the collected data.

The low water fraction of the elongated bubble of strong cavitation becomes also clearly visible by looking at the pixel values along a line through the image (black line in figure 14). The line thereby cuts through the bubble (see CT image in figure 14). In the diagram, in which the pixel values are plotted over x (see diagram in figure 14), several characteristic regions can be identified. On the left of the diagram the low level of liquid water can be seen in the curve within the wall region (indicated with 'W'). This is also visible in the CT-image of figure 14. On the right, the water fraction does not go down to the level of the left side, which can also be seen in the images and might be the reason of the limited angle artefact (see section 5). Between the wall regions, PV is mostly within the range of the measured pixel values for water and air. The peak above the measured value for water inside the channel is a reason of a motion artefact ('A' in figure 14). Outside the channel, two peaks near the wall region are also visible, which were caused by the filter of the back-projection algorithm. After all, the strong bubble ('S' in figure 14) is well pronounced and the diagram indicates that there is no liquid water present in this area. This very low attenuation level supports the thesis that there is no liquid water inside the imaged structure, which appears as elongated bubble.

Another event, which occurs within the investigated flow, is depicted in figure 15. By imaging the cavitation structures with a scientific high-speed camera at a frame rate of 9000fps (photographs in figure 15), a rapid radial transport of bubbly fluid is visible. Because the event occurs very suddenly and the fluid seems to explode out of the LC, the authors named the event 'explosion'. The reason for these explosions becomes obvious by looking at the CT images.

The CT images of figure 15 were taken within a time interval of 0.5 ms. In the centre of the images, a cavitation zone is visible inside the LC (black arrows in figure 15), which is not strongly connected with the cavitation zone near the wall and is growing rapidly from plane 1 to plane 2. Because the cavitation is occupying a large volume, the remaining liquid water is rapidly shifted towards the wall, due to continuity reasons. From the outside, this looks like the bubbly water explodes out of the LC (see photographs of figure 15).
Figure 14. Diagram of the pixel values (PV) extracted from a CT image (top); position of the scan \( z = 33 \) mm; black line in the image indicates position of the PV extraction, dashed line ...PV of liquid water, dash-dot line ...PV of air; A ...artefact, W ...wall region, S ...strong cavitation.

Figure 15. CT image of an Explosion event; photographs with marked planes (top) and CT images (bottom); (a) 1st plane, (b) 2nd plane; position of plane 1 \( z = 24 \) mm, plane distance 13 mm, \( \Delta t = 0.5 \) ms; pseudocolours indicate amount of liquid water, \( \alpha \); arrows ...growing cavitation zone; dotted box ...area with large amount of liquid water; photographs shows location of measurement planes.
This example greatly demonstrates that high-speed CT can provide further, important information on cavitation and flow development. But it shows also that the best results can be achieved by combining high-speed x-ray CT imaging with other established high-speed imaging techniques for cavitation research, such as high-speed videography.

The last image (figure 16) of this section shows three independent photographs and CT images in the collapse region of the channel (see figure 6) at \( z = 91 \) mm. From the photographs it is clearly visible that the cavitation does not stop immediately at a certain position of the channel. Cavitation clouds occasionally come out of the strong cavitation region and being transported downstream (first and third photograph in figure 16). After these clouds are washed downstream or just vanished due to the rising pressure at the very end of the cavitation channel, only pure liquid water, without cavitation, is visible in the photograph (second photograph in figure 16).

As expected from the averaged CT image of this zone, the high-speed CT images also show very light or no cavitation. Further, the CT images of figure 16 show similar phenomena as the photographs of figure 16. While in the first and third CT image, areas of light cavitation are visible, the second image shows only liquid water. Unfortunately, it is hardly possible to capture the small and highly dynamic cavitation structures in the collapse region, due to the relatively long measurement time of 1 ms. But even with this drawback, a spot of strong cavitation could be identified in the first CT-image of figure 16 (black arrow). At this point it has to be mentioned that no cavitation structure is leaving the cavitation channel. The whole process of initialisation and growing of the cavitation till the final collapse of the structures occurs only within the cavitation channel. That is a difference compared to high pressure Diesel injection nozzles where cavitation structures are leaving the nozzle hole, depending on the cavitation number.

The last example of light cavitation in the collapse area shows, that in case of light cavitation, conventional imaging or high-speed videography is still the best tool for imaging cavitation structures, but from the CT some additional informations about the strength of the cavitation can be derived.

In summary it can be said that x-ray CT is no substitution for the established techniques in cavitation research but it can provide some valuable, additional information about the occurring phenomena in the field of cavitation.

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![Figure 16. Photographs and CT image in the collapse region; the line in the photographs show the measurement position of plane 2 of the CT at the very end of the cavitation region at \( z = 91 \) mm. Pseudocolours indicate amount of liquid water, \( \alpha \); arrow shoes spot of strong cavitation.](image)
6. Concluding remarks

In the present study, a strongly cavitating nozzle flow, which shows high dynamics and turbulence, was investigated with high-speed x-ray computed tomography in order to show the potential of this technique in cavitation research. First, averaged images were calculated and compared with results obtained from a medical CT with the same nozzle, published in Bauer 2012 [15]. Like the medical CT, the ROFEX scanner was able to image cavitation structures inside the cavitation zone, which cannot be captured with conventional imaging techniques. Although the images, obtained with the high-speed CT, were time averaged as well, the dynamic structure of the cavitation and the development of the cavitation inside the nozzle could be captured, due to the short averaging interval. Furthermore, typical structures, like e.g. an elongated cavitation bubble completely filled with vapour, could be identified, because of the two measurement planes of the ROFEX. In addition, the reason for the presented explosion event could clearly be identified as a rapidly growing cavitation area, which was not visible from outside. This area causes a fast and radial transport of liquid water into the void region near the wall. This is a very good example how external visible flow phenomena result from internal cavitation flow structures.

To draw a conclusion, the results show that high-speed x-ray CT is a helpful tool for cavitation research. But, the results also show that the best way for visualizing cavitation flows is a combination of high-speed CT and high-speed videography.

For further investigations, the focus should be on improvement of the calibration technique for using the high-speed CT technique in cavitation research and to analyse the CT images quantitatively. Further a simultaneous recording of high-speed CT and videography has to be included in the experiments. Another big task would be additional measurement planes for capturing CT images, in order to get a much better view on the evolution of cavitation structures, even in pseudo 3D. Furthermore, the possibility of deriving velocity information from image sequences of ROFEX CT, using cross correlation algorithm, should be investigated and implemented in the post-processing of the images.

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ORCID iDs

D Bauer @ https://orcid.org/0000-0001-5089-7061

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