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Originally published:

November 2019

**Journal of Fluids Engineering - Transactions of the ASME 142(2020)4, 041502**

DOI: <https://doi.org/10.1115/1.4045497>

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# Ultrafast X-ray CT imaging for hydrodynamic investigations of gas-liquid two-phase flow in centrifugal pumps

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## Abstract

Gas entrainment into centrifugal pumps decreases pump performance and may raise safety issues, e.g. through insufficient cooling. Although there is some phenomenological knowledge in form of correlations between operating parameters and pump performance a further understanding via direct observation of the gas-liquid mixture was so far not possible. In this paper, we demonstrate the capability of ultrafast X-ray computed tomography (UFXCT) to disclose gas-liquid two-phase flow dynamics in the impeller region of a centrifugal pump mockup. Experiments were performed for gas injection at impeller speeds between 1300 rpm and 1600 rpm. We analyzed the time-resolved X-ray images with respect to the gas distribution and compared them with time-averaged image data of a real pump obtained earlier with gamma-ray tomography.

**Keywords:** centrifugal pump, gas-liquid two-phase flow, ultrafast X-ray computed tomography

## 25 1. Introduction

26 Centrifugal pumps are used in many industrial applications. They are economic and highly  
27 reliable, provide smooth and steady operation and offer low energy consumption. They are  
28 important primary components, e.g. in oil recovery plants to lift up crude oil to the surface  
29 and to convey it to petroleum production facilities [Barrios et al., 2011; Sabino et al., 2016;  
30 Bellary et al. 2018]. Furthermore, centrifugal pumps are also used in emergency cooling  
31 circuits of nuclear power plants [e.g.: Schultz et al, 2006; Stosic et al, 2008; Sato et al.,  
32 2009]. If water is taken there from reservoirs with free surfaces, the gas phase may  
33 undesirably become sucked into the pump. This reduces the flow rate of the pump and, thus,  
34 constitutes an important safety risk. To avoid and to handle such critical situations, it is  
35 necessary to investigate and understand the hydrodynamics of the two-phase flow inside  
36 centrifugal pumps. Furthermore, numerical fluid dynamics simulations may help in the future  
37 to improve centrifugal operations in their design. Hence, experimental data about two-phase  
38 flow in pumps is of high value.

39 Before starting with a review of the state of the art, relevant physical quantities for pumps in  
40 single and two-phase operation are introduced. A pump is characterized by its hydraulic  
41 power  $P_{hyd} = Q_L \rho g h$  which is the power imparted by the pump on the fluid to increase its  
42 velocity and pressure.  $Q$  is the flow rate,  $\rho$  the fluid density,  $g$  is gravitational acceleration  
43 and  $h$  is the pump head. The pressure drop over the pump is  $\Delta p$ . For a gas-liquid flow we  
44 denote local cross-sectional values of gas holdup in the pump by the symbol  $\alpha$ , while the  
45 inlet volumetric gas fraction is  $\varepsilon = \frac{\dot{V}_G}{\dot{V}_L + \dot{V}_G}$  with  $\dot{V}_G$  and  $\dot{V}_L$  being the gas and liquid volumetric  
46 flow rates.

47 In 1974 Murakami et al. already investigated the behavior of entrained air bubbles and their  
48 effect on the pump performance distinguishing prime, head, discharge and efficiency. They  
49 investigated a radial semi-open impeller type pump and discovered that for smaller  
50 volumetric air entrainment ( $\varepsilon \leq 0.04$ ) the performance reduces continuously with increasing  $\varepsilon$   
51 whereas for higher air entrainment ( $\varepsilon > 0.04$ ) the performance falls rapidly and discontinuities  
52 appear that change the flow pattern in the impeller abruptly. Furthermore, they developed  
53 and validated a theoretical approach for modeling the effects of the admitted air on the flow  
54 behavior and for calculating the performance curves under these two-phase flow conditions.

55 Thereafter, several other experimental and numerical studies have been conducted to  
56 investigate the performance of centrifugal pumps under varying operating conditions. In  
57 1999, observations on a full-size nuclear reactor primary coolant pump operated at two-  
58 phase flow conditions have been reported by Chan et al. (1999). They disclosed the effects

59 of inlet flow temperature and initial flow conditions on the two-phase performance for very  
60 high gas entrainment ( $\varepsilon$  up to 0.40). In addition, Narabayashi et al. (1986) performed  
61 experiments using three scaled model pumps to examine the effects of specific pump speeds  
62 and characteristics of the high-void two-phase flow on the performance of centrifugal pumps  
63 in nuclear cooling circuits. The experimental analysis was accompanied by a data evaluation  
64 using the Transient Reactor Analysis Code (TRAC). They provided data, which are required  
65 to evaluate the primary loop recirculation (PLR) during a loss-of-coolant accident (LOCA).  
66 Pak et al. 1998 performed numerical analyses using three-dimensional finite volume method  
67 (FVM) to predict the flow characteristics of air-water two-phase turbulent flows in a  
68 centrifugal pump impeller and compared it with experimental data for additional gas phase,  
69 pressure and velocity in the impeller region. Here, the modeling of air-water two-phase  
70 mixture was proposed based on a bubbly flow model while the standard k- $\varepsilon$  turbulence model  
71 was applied for the liquid phase only. Müller et al. 2015 evaluated the capability of the mono-  
72 dispersed multi-phase model in ANSYS CFX to predict the flow of liquid-gas mixture in radial  
73 pumps. In other studies, consequences of two-phase flow due to cavitation have been  
74 investigated [Duplaa et al., 2013; Tan et al., 2013; Coutier-Delgosha et al., 2003]. The study  
75 of Caridad et al. (2008) focused on the influence of bubble diameter and gas flow on the  
76 pump operation. Furthermore, Murakami et al., 1977 and Minemura et al., 1980, who  
77 theoretically and experimentally investigated the movement of entrained air bubbles with  
78 respect to the resulting change in pump performance, studied the physical behavior of one or  
79 few bubbles in an impeller. They also numerically calculated trajectories of isolated air  
80 bubbles in an impeller and compared it to experimental high-speed camera observations. In  
81 2001, Amoresano et al. presented an experimental approach to characterize the two-phase  
82 flow field inside the impeller to understand the interaction between the gas and liquid phases  
83 under different inlet conditions. Therein, a correlation between gas-liquid structures and the  
84 energy dissipation phenomena in a centrifugal pump could be observed.

85 From the experimental side it is worth mentioning that conventional X-ray CT has already  
86 been applied to centrifugal pumps in the past, e.g. by Hassan et al. (2008). However, the  
87 spatial resolution was not sufficient which caused difficulties for quantitative code validation.  
88 High-speed videometry is another very popular and widely used method [Amoresano, et al.,  
89 2001; Barrios et al., 2011; Sabino et al., 2016]. However, its application needs an optical  
90 access to the flow as well as a low gas holdup.

91 Recently, our group has employed gamma-ray computed tomography (GammaCT) to study  
92 gas accumulations in an industrial centrifugal pump with a special approach, called time-  
93 averaged rotation-synchronized gamma-ray computed tomography [Bieberle et al., 2007].  
94 The studies disclosed a gas accumulation in form of large gas pockets inside the impeller

95 chambers that is continuously increasing with the amount of gas entrainment [Schäfer et al.,  
96 2015; Neumann et al., 2016; Schäfer et al., 2017]. However, though gamma-ray imaging  
97 provides high resolution and very good phase fraction quantification [Bieberle et al., 2015]  
98 the reconstructed images contains only time-averaged information over approximately 600 s  
99 and hence no conclusions about the flow dynamics can be drawn.

100 Therefore, in this study we qualified ultrafast X-ray computed tomography (UFXCT) [Fischer  
101 et al., 2008] for dynamic studies of gas entrainment in an industrial-scale impeller mockup.  
102 This imaging technique has already been successfully applied for two-phase flow  
103 investigations in heated rod bundles [Barthel et al., 2013], structured packings [Janzen et al.,  
104 2013], ceramic foams [Zalucky et al., 2017a; Zalucky et al., 2017b], helical static mixers  
105 [Rabha et al., 2015], spout fluidized beds [Bieberle et al., 2016] and monoliths [Schäfer et al.,  
106 2016]. It allows contactless imaging of the two-phase distribution with high temporal and  
107 spatial resolution. However, since the penetration ability of X-rays is lower than that of  
108 gamma radiation, e.g. Cs<sup>137</sup>, we must revert to a mock-up instead of an original industrial  
109 centrifugal pump. This mock-up comprises all the geometric features of an original pump but  
110 consists of lighter materials. With this mock-up, studies for different gas phase entrainment  
111 rates and with disperse and swirling gas-liquid inlet flow have been performed [Schäfer et al.,  
112 2019]. The corresponding two-phase flow in the impeller area has been scanned with a rate  
113 of 2,500 cross-sectional images per second. Additionally, the relative pressure at the suction  
114 side and the differential pressure across the pump were simultaneously recorded.

## 115 **2. Materials**

### 116 **2.1 Experimental setup**

117 The experimental setup for gas-liquid investigations in an impeller is shown in Figure 1a. It  
118 consists of a flow loop wherein a gas-liquid two-phase flow is continuously conveyed by the  
119 centrifugal pump mockup (Figure 1b). The impeller is made from polyamide and is  
120 manufactured by rapid prototyping technology. Its geometry is based on the original impeller  
121 geometry of an Etachrom BC 032-160/074 C11 (KSB) as earlier studies with gamma-ray CT  
122 were conducted at this type of pump [Schäfer et al., 2015, Neumann et al., 2016]. The most  
123 relevant geometric data are given in Table 1. The impeller design is shown in Figure 2.  
124 Furthermore, the entire CAD drawing data set is published by Schäfer et al. (2019).

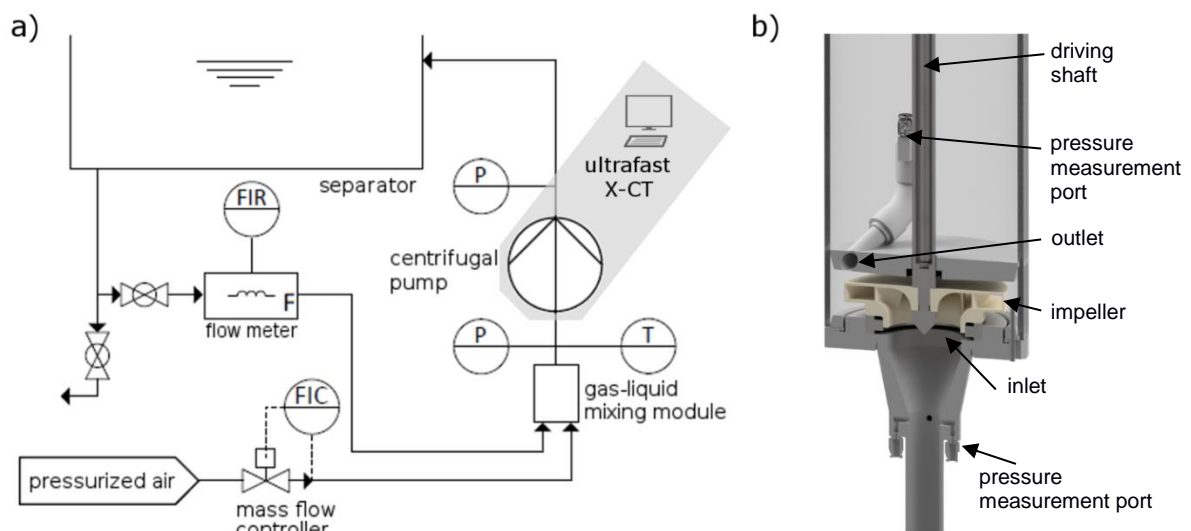
125 A defined initial gas-liquid two-phase inlet flow is generated upstream of the impeller by a  
126 gas-liquid mixing module (see Figure 1a). In the experiments tap water and de-oiled  
127 pressurized air is used. The liquid is supplied from a 170 l reservoir, which also acts as a  
128 gas-liquid phase separator. The liquid temperature is controlled to 21 °C± 0.5 K during all

129 experiments. The liquid flow rate is measured upstream the mixing module by an inductive  
 130 flow meter (MAG 1100, Siemens). The gas entrainment rate  $\varepsilon$  ( $0 \leq \varepsilon < 1$ ) is continuously  
 131 adjusted and the required gas flow rate  $Q_G$  is controlled by an air mass flow controller  
 132 (FMA2600, Omega Newport), which is triggered by a programmable logic controller (SPS-  
 133 ILC350ETH, Phoenix Contact) considering the current liquid flow rate  $Q_L$  according to

$$Q_G = \frac{\varepsilon}{1-\varepsilon} Q_L. \quad (1)$$

134 Furthermore, two different inlet two-phase flow regimes can be selected using a self-  
 135 developed gas-liquid phase mixing module. These are dispersed bubbly two-phase flow and  
 136 swirling two-phase flow with a stable gas core. Both flow regimes are typical for gas  
 137 entrainment caused by hollow vortices [Hecker, 1981]. The flow loop is additionally  
 138 instrumented with two pressure sensors to measure the relative pressure at the suction side  
 139 (PXM419, Omega Newport) and the differential pressure across the pump (PD23, Omega  
 140 Newport). The impeller itself is rotated by a driving shaft (see Figure 1b) that is again  
 141 connected to a servomotor (ACA 90 S-4 / IE2, ecoDrives) that provides a selectable constant  
 142 rotational speed between 1300 rpm and 1600 rpm. The final effective rotational speed is  
 143 additionally directly measured using a Hall-effect sensor (GS105502, ZF Electronics), which  
 144 is placed close to the driving shaft. This signal is later on used for exact image reconstruction  
 145 of the rotating impeller.

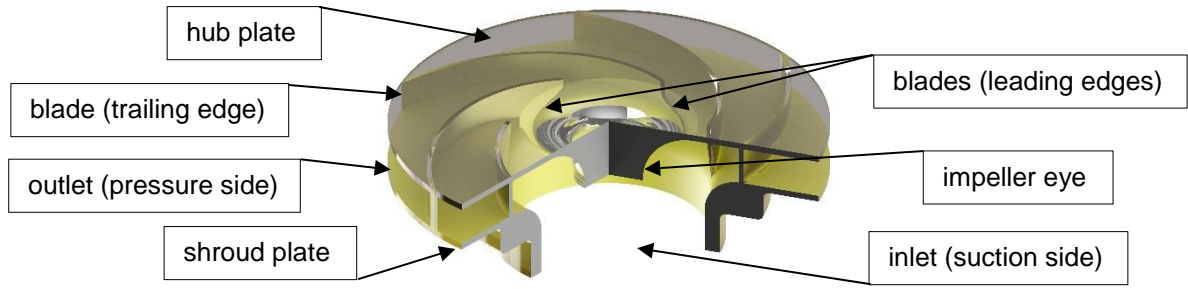
146



147

148 **Figure 1:** a) Schematic of the experimental setup and b) detailed view on the test section with the  
 149 pump impeller.

150



151

152

**Figure 2:** Semi-transparent visualization of the manufactured impeller.

153

**Table 1:** Geometric specifications of the impeller.

	property	value
	impeller inlet diameter $d_1$	54.0 mm
	impeller outlet diameter $d_2$	136.0 mm
	number of blades	6
	impeller inlet blade angle $\beta_1$	$18.2^\circ$
	impeller outlet blade angle $\beta_2$	$26.8^\circ$
	thickness of blades	2.0 mm
	chamber height (distance between hub plate and shroud plate)	12.0 mm
	impeller eye diameter (in the scanning plane)	32.0 mm

154

## 155 2.2 Ultrafast X-ray CT imaging

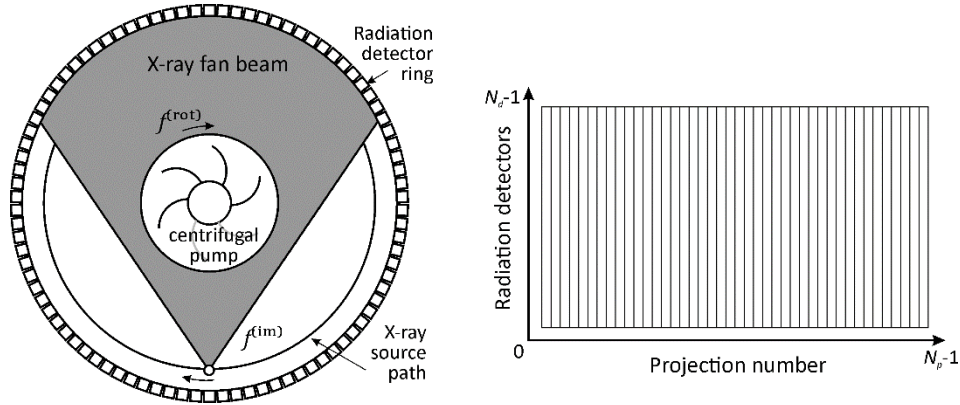
156 Ultrafast X-ray computed tomography (UFXCT) has been applied to visualize the gas-liquid  
 157 phase distribution quantitatively inside the impeller region. The CT scanner comprises two  
 158 imaging planes with  $N_d = 432$  detector elements each and is able to image objects up to  
 159 190 mm in diameter with an in-plane spatial resolution of about 1 mm. An imaging frequency  
 160 of  $f^{(im)} = 2,500 \text{ Hz}$  (or frames per second) and single-plane scanning operation mode has  
 161 been selected for gas-liquid phase investigations in the rapidly rotating impeller area. For  
 162 image reconstruction, filtered back projection method is used [Hampel in Wang et al., 2015].

163 In contrast to conventional X-ray CT, in ultrafast X-ray CT the radiation source is artificially  
 164 rotated around the impeller mockup with the aforementioned frequency  $f^{(im)}$  while projection  
 165 data is continuously acquired with a fixed frequency of  $f^{(samp)} = 1 \text{ MHz}$  using fixed  
 166 positioned radiation detector rings (see Figure 3). Thus, in total  $N_p = 400$  projections are  
 167 obtained from the impeller that rotates during the CT scans with its own frequency  $f^{(rot)}$ .



168 Thus, additional data pre-processing must be performed to avoid motion blurring in the  
 169 reconstructed images.

170



171

172 **Figure 3:** Sketch of ultrafast X-ray CT applied for investigation on rapidly rotating objects.

173

174 There are two ways to obtain image sequences for the rotating system. Either reconstruction  
 175 is done in the fixed system and subsequently images are rotated or the projection data is  
 176 shifted in the angular space according to the actual impeller angle, which is derived from the  
 177 zero-crossing signal of the Hall sensor. The latter approach is to be preferred as interpolation  
 178 is avoided. Assume we have a time interval  $\Delta T^{(rot)}$  between two subsequent zero-crossing  
 179 signals defining the time for one impeller revolution. Then, the impeller's angular progress  
 180 within one image frame is

$$\Delta\varphi = 2\pi f^{(im)} \Delta T^{(rot)}. \quad (2)$$

181 Hence, the projection data has to be shifted by  $N_p f^{(im)} \Delta T^{(rot)}$  angular samples to obtain an  
 182 image in the rotating frame.

183 Another specific feature of the reconstruction procedure is that we account for the impeller  
 184 rotation during the period where projection data for one image is acquired. Between two  
 185 projections taken with  $T^{(samp)} = 1/f^{(samp)} = 1 \mu s$  temporal displacement the impeller moves  
 186 a small angle of  $2\pi T^{(samp)}/\Delta T^{(rot)}$ . This angular displacement is encountered by another  
 187 data shift during reconstruction and thus, rotational fluctuations and drifts are compensated  
 188 which guarantees cross-sectional images with no motion blurring.



### 189 2.3 Determination of local gas holdup and gas-liquid interface

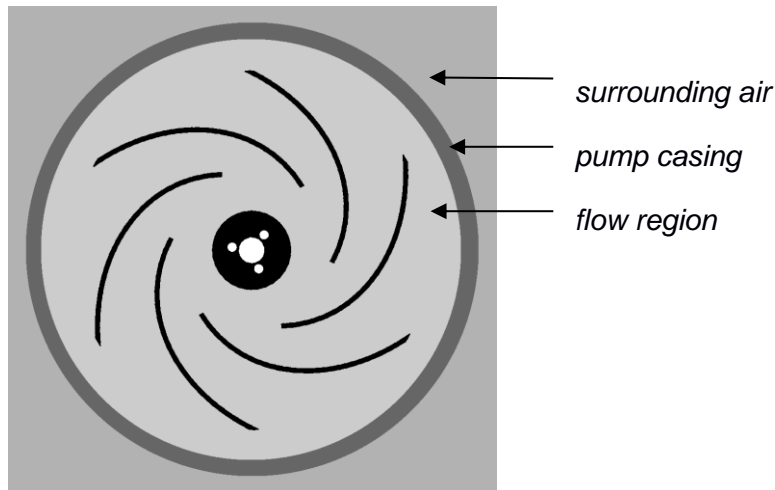
190 Result of image reconstruction is a stack of images whose pixels contain the local X-ray  
191 attenuation values  $\mu_{i,j,k}^{(\text{rec})}$ . Thereby  $i$  and  $j$  denote the spatial pixel index and  $k$  the image  
192 number within the temporal sequence. The reconstructed linear attenuation coefficient is  
193 typically prone to errors coming from beam hardening, radiation scattering but also slight  
194 electron beam misalignments. Therefore, we normalize the values with the help of average  
195 gray values from image regions with known linear attenuation. Such are the average  
196 attenuation coefficient  $\bar{\mu}^{(\text{P})}$  of the acrylic pump casing and  $\bar{\mu}^{(\text{G})}$  the average attenuation  
197 coefficient of the “gas-filled” pixels outside the pump (see Figure 4). With that, the  
198 normalization is given as

$$\mu_{i,j,k} = \frac{\mu_{i,j,k}^{(\text{rec})} - \bar{\mu}^{(\text{G})}}{\bar{\mu}^{(\text{P})} - \bar{\mu}^{(\text{G})}}. \quad (3)$$

199 From this, we compute the gas holdup values  $\alpha_{i,j,k}$  from the attenuation data according to

$$\alpha_{i,j,k} = 1 - \frac{\mu_{i,j,k}^{(\text{TP})}}{\mu_{i,j}^{(\text{L})}}, \quad (4)$$

200 where  $\mu_{i,j,k}^0$  represents the CT data sets obtained at gas-liquid two-phase flow (TP) and liquid  
201 single-phase flow (L), respectively.



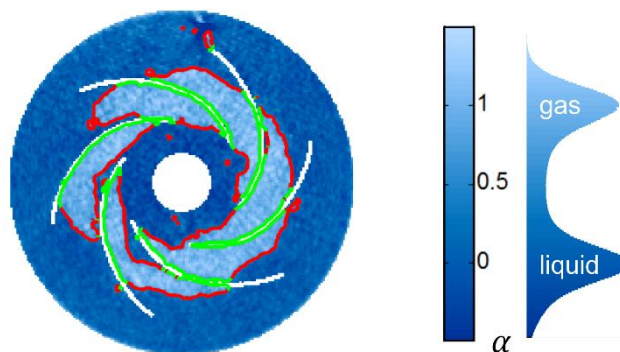
202 **Figure 4:** Schematic of material distribution within the reconstructed cross-sectional images used  
203 for image improvement.

204

205 Note, with reference to the color bars in the figures below that due to noise in the  
206 reconstructed images the calculated gas holdup may statistically deviate from its mean  
207 value. This may lead to unphysical local phase fraction values outside the range [0,1].  
208 Usually, data is cut to the physical minimal or maximal value. However, as this occurs errors  
209 in calculation of space and time averaged holdups those values are left as they are.

210 For the extraction of the gas interface, an algorithm firstly published by Li et al. (2011) and  
211 adapted for two-phase flow interface extraction in Sohr et al. (2019) has been applied. The  
212 algorithm is based on the level set method with application to image segmentation and  
213 considers intensity inhomogeneity within the image, which may occur in X-ray CT imaging  
214 due to scattering and beam hardening. The resulting gas interface can be divided into gas-  
215 liquid (free) and gas-solid (bounded by the impeller structure) interface sections. To  
216 distinguish both of them, the mask of the impeller is applied. An interface length parameter,  
217 which is corresponding to interfacial area, is then calculated as the sum of distances  
218 between neighboring contour points, i.e. the length of a piecewise linear approximation of the  
219 contour, which, however, is only an approximation on a sub-pixel scale. In Figure 5 a  
220 representative illustration of a cross-sectional gas holdup image with indicated gas-liquid  
221 (red) and gas-solid interface (green) is shown.

222



223

224 **Figure 5:** Cross-sectional gas holdup image with indicated gas-liquid (red) and gas-solid interface  
225 (green).

226

## 227 2.4 Experimental procedure

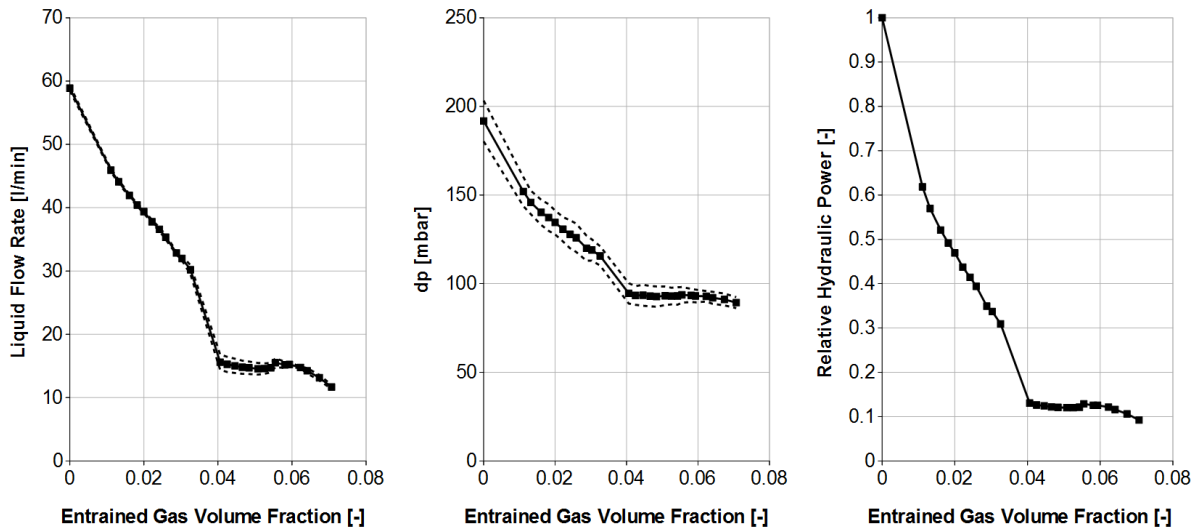
228 The experimental procedure described next has been performed for all experimental points,  
229 that is, 117 operating points in total (for the full experimental data set see Schäfer et al.  
230 (2019)). However, in this paper only an exemplary data set at 1480 rpm impeller speed,

231 dispersed gas phase injection and different gas flow rates is used for discussion. Initially, the  
 232 rotational speed of the impeller is set to constant nominal rotational speed of 1480 rpm.  
 233 Subsequently, disperse gas entrainment (bubbly two-phase flow) is adjusted and varied in  
 234 discrete steps of  $\Delta\varepsilon = 0.002$  in the range from  $\varepsilon = 0.008$  to  $\varepsilon = 0.058$ . The latter corresponds  
 235 to the maximum value prior to severe performance drop.

236 The corresponding performance curves, that is for liquid conveying rate  $Q_L$ , differential  
 237 pressure  $\Delta p$  across the pump and relative hydraulic power  $P_{\text{hyd,rel}}$

$$P_{\text{hyd,rel}}(\varepsilon) = \frac{P_{\text{hyd}}(\varepsilon)}{P_{\text{hyd}}(\varepsilon = 0)} = \frac{Q_L(\varepsilon) \cdot \Delta p(\varepsilon)}{Q_L(\varepsilon = 0) \cdot \Delta p(\varepsilon = 0)} \quad (5)$$

238 are shown in Figure 6.



239

240 **Figure 6:** Performance curves of the investigated centrifugal pump mockup.

241

242 Prior to the experiments, for each gas entrainment value, the conveyance curve is checked  
 243 for stability over the time, to be sure that the pumping system is operated in steady-state  
 244 condition. Subsequently, UFXCT scanning is performed for an interval of 5 s, which gives  
 245  $K = 12,500$  cross-sectional images of the impeller. The residual temporal fluctuations of the  
 246 liquid flow rate and the differential pressure during the tomographic scans have been found  
 247 to be between  $\pm 0.46\%$  and  $\pm 7.86\%$  (relative to mean liquid flow rate) and  $\pm 3.19\%$  and  
 248  $\pm 6.36\%$  (relative to mean differential pressure), respectively and are represented as dashed  
 249 lines in the corresponding diagrams in Figure 6.

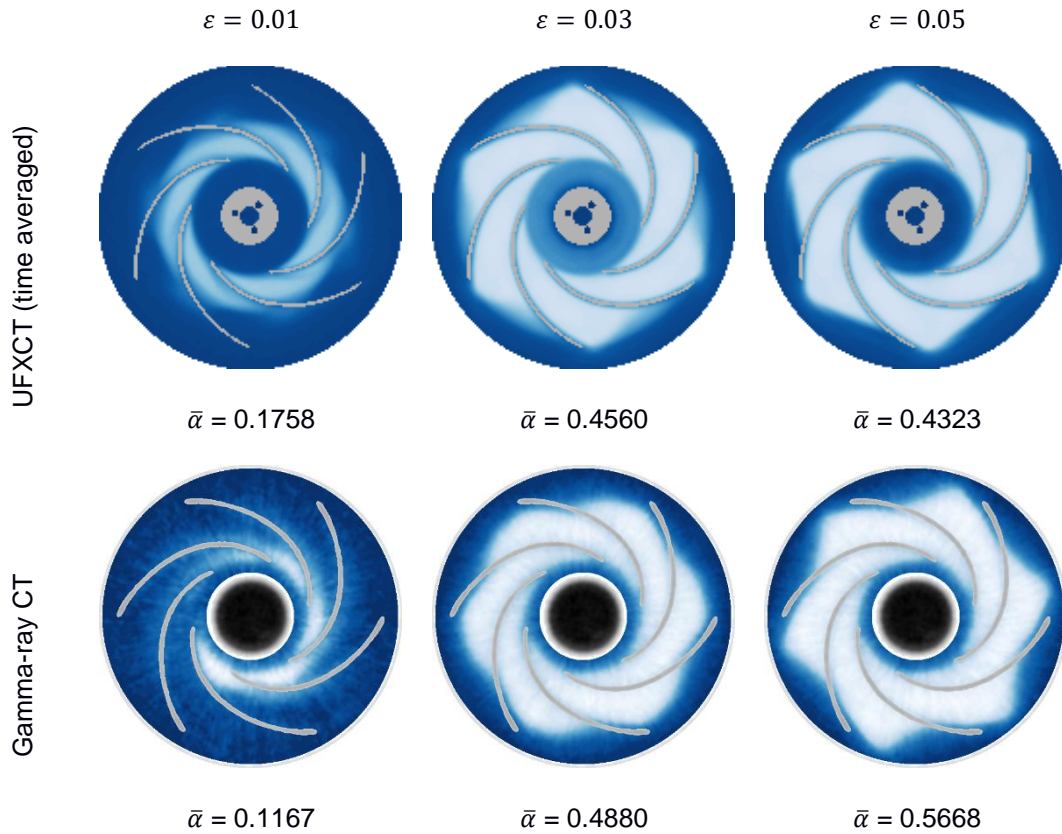
250

251 **3. Results**

252 **3.1 Comparison with gamma-ray CT measurements**

253 Initially, the function of the impeller mockup and, therefore, the transient behavior of the two-  
254 phase fraction distribution have been evaluated to conform to the already existing  
255 tomographic images obtained from the original industrial pump [Schäfer et al., 2015], where  
256 gamma-ray CT scans provided single time-averaged (600 s) but angle-resolved images of  
257 the two-phase distribution. Therefore, the three corresponding UFXCT scans have been  
258 temporally averaged (5 s) over all  $K$  images. As can be seen in Figure 7 the comparison  
259 yields a strong agreement, with minor differences in the overall gas holdups  $\bar{\alpha}$  originate  
260 (beside others) that may occur from slightly different applied impeller area mask sizes.

261



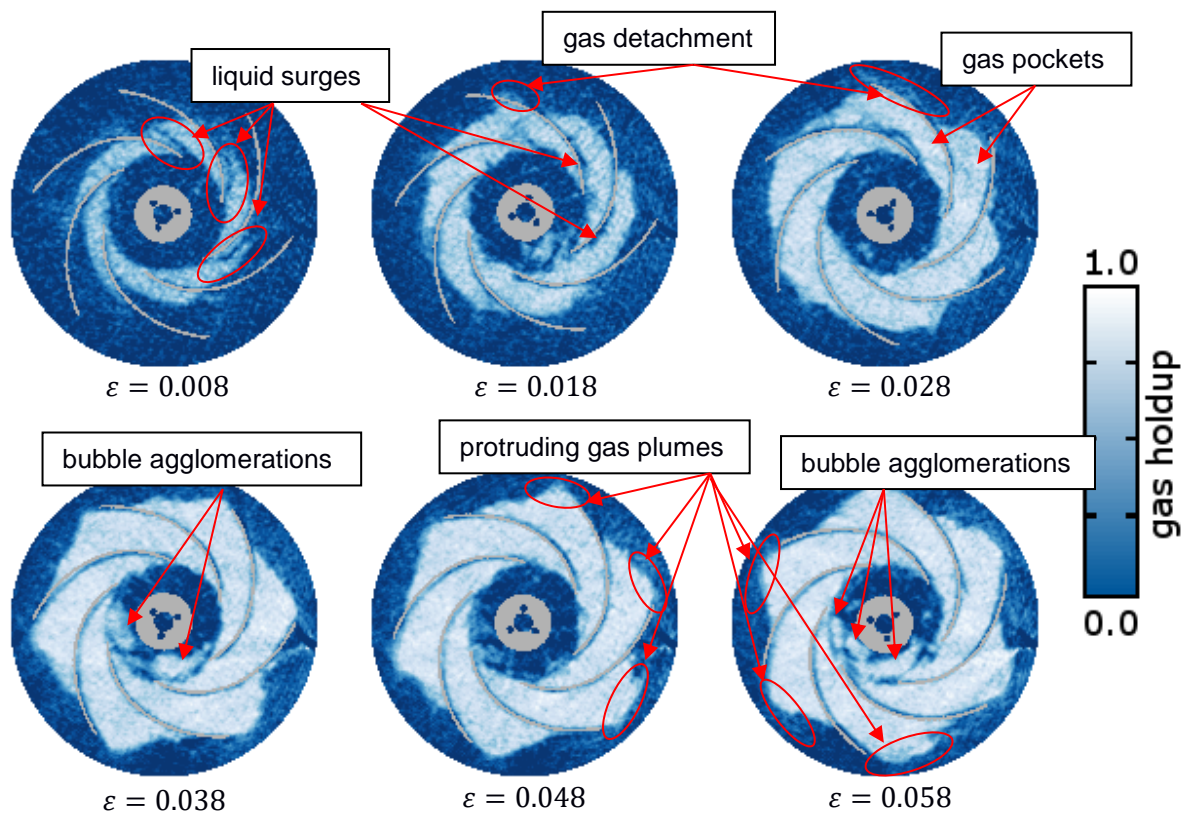
262 **Figure 7:** Comparison of selected cross-sectional and time-averaged gas holdup distributions in a  
263 rotating impeller at 1480 rpm using UFXCT and gamma-ray CT [Schäfer et al., 2015]  
264 technique. The gas phase is injected in dispersed form.

265

266 **3.2 Qualitative analysis**

267 In Figure 8, a selection of the obtained instantaneous UFXCT tomographic images is shown.  
268 Furthermore, the corresponding image sequences (image sequences 1-6) are provided as  
269 supplementary material to this publication. They provide an impression of the way certain  
270 gas-liquid structures form out in the heavily agitated mixture. For example, small lamella-like  
271 structures of pure liquid are observable at the pressure side of the blades from time to time.  
272 Here, liquid is shooting through the accumulated gas pockets in short-term surges. This is  
273 observed especially for lower gas entrainment. Furthermore, at higher gas entrainment, large  
274 bubbles are temporally visible in the area of the impeller eye. These bubble agglomerations  
275 are stable in position and shape for a certain time. Since they are upstream of the inlets of  
276 the impeller chambers, they indicate liquid transport blockage at these positions. In the area  
277 of the chamber outlets gas detachment is observed. Here, small gas bubbles are detached  
278 from the accumulated gas pockets. In the impeller outlet areas, protruding gas plumes have  
279 been detected for higher gas entrainment ( $\varepsilon \geq 0.03$ ). These gas plumes are growing out of  
280 the chambers along the suction sides of the blades into the flow area outside the impeller.

281



282

283 **Figure 8:** Characteristic gas-liquid flow patterns inside the impeller under increasing gas entrainment  
284 conditions and at 1480 rpm.



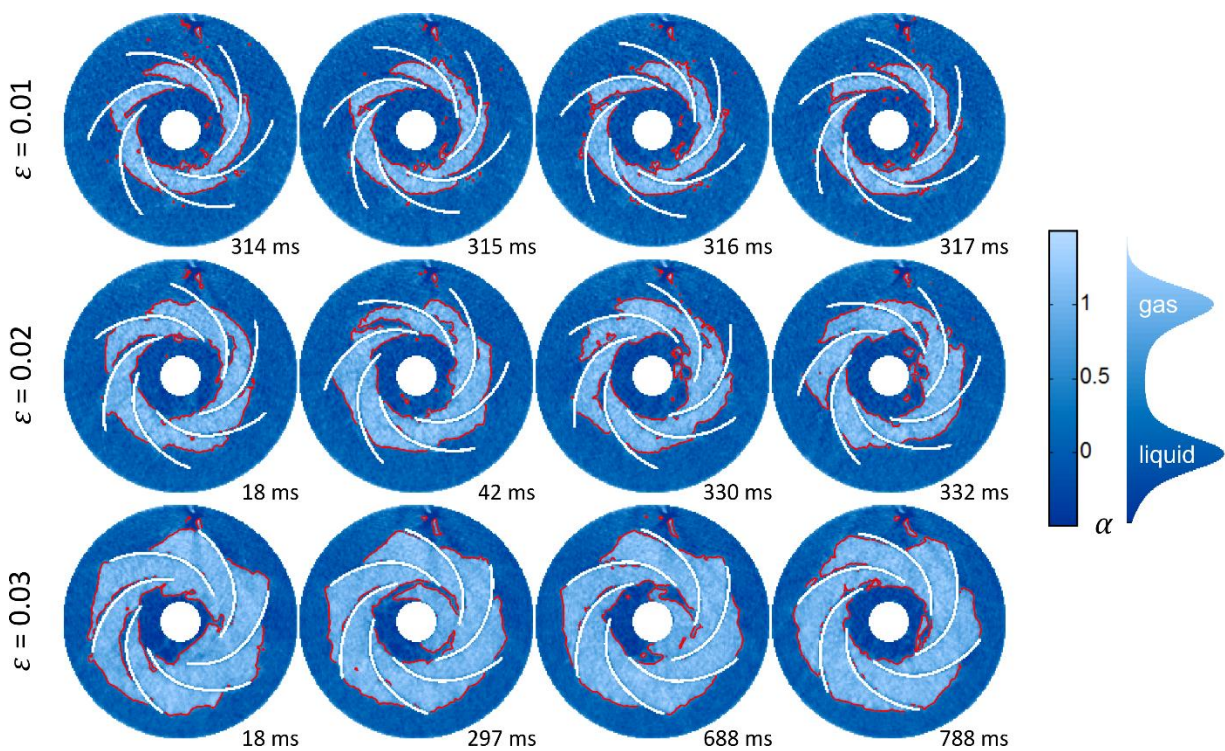
285

### 286 3.3 Quantitative analysis of the image sequences

287 From the gas holdup images, gas interfaces and their length (corresponding to interfacial  
288 area) are determined. A selection of images with the extracted gas-liquid interface is shown  
289 in Figure 9. As can be seen, relevant structures including small bubbles and thin liquid  
290 surges are captured. Especially the latter are clearly distinguished from gas-solid interfaces  
291 with no liquid in between.

292 A quantitative analysis of the gas-liquid interface (Figure 10) reveals different trends of gas-  
293 liquid and liquid-solid interface. While the gas-solid interface correlates with injected gas flow  
294 rate, the free gas-liquid interface remains nearly constant in the considered cases.

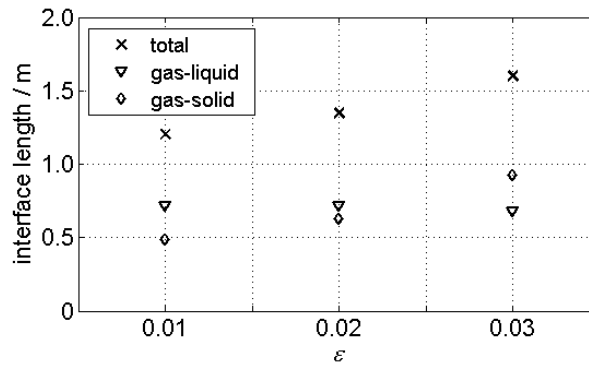
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296

297 **Figure 9:** Extracted gas-liquid interface (indicated in red) for three inlet gas entrainments at  
298 different points in acquisition time.

299



300

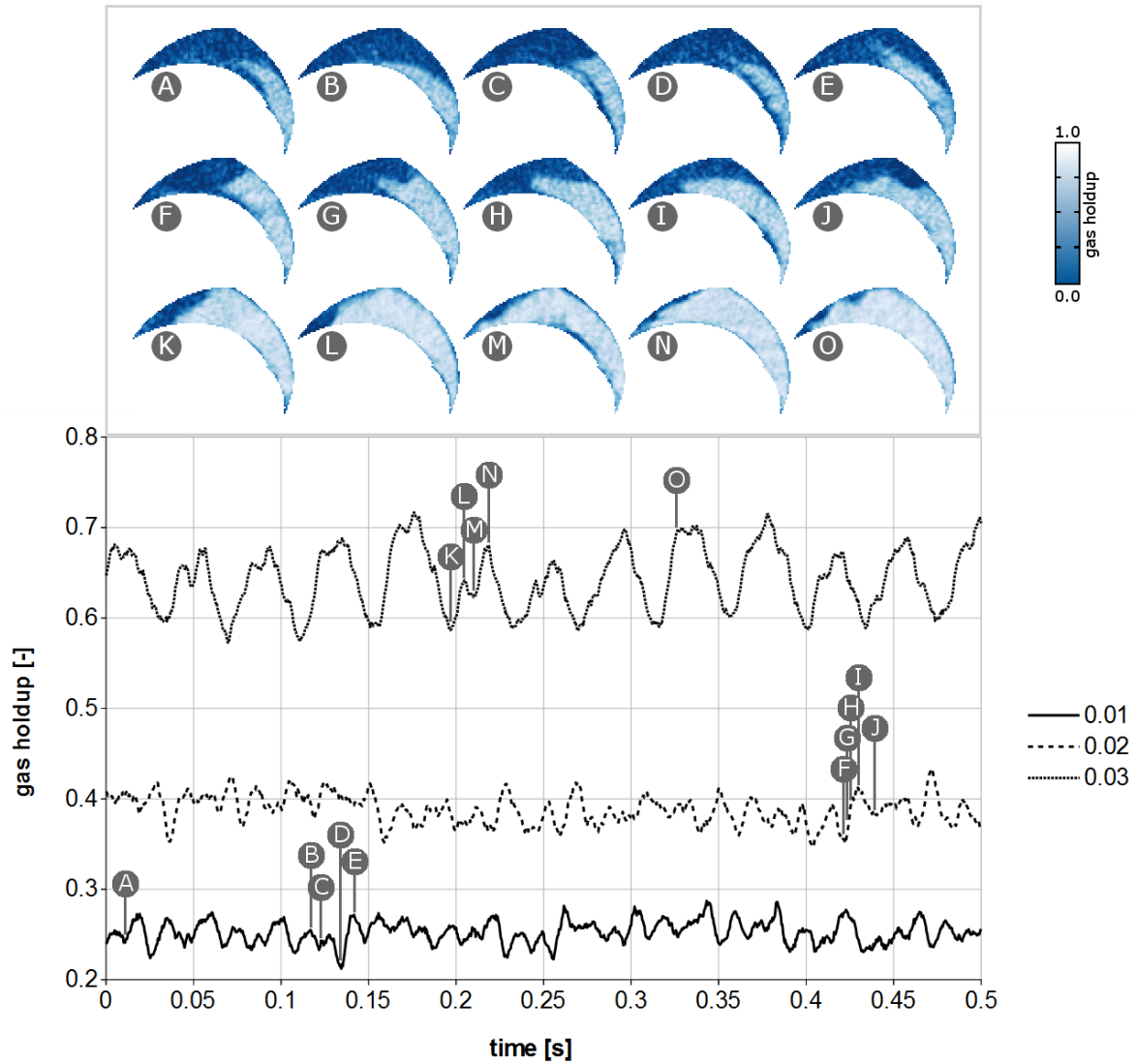
301 **Figure 10:** Averaged length of the gas interface within the cross-section divided into the gas-liquid  
 302 interface and gas-solid interface.

303

304 Taking the obtained tomographic images and selecting only the flow area of one impeller  
 305 chamber gives a detailed view on the accumulated gas pockets and the gas-liquid interfaces  
 306 (Figure 11 A-O). Looking at the images qualitatively, different shapes of the accumulated gas  
 307 pockets are clearly visible. Furthermore, areas with temporal changing phases can be  
 308 discovered. That is, intensive phase interactions between liquid and gas pockets occur.  
 309 Furthermore, a temporal shifting of the gas pockets, especially at the suction side of the  
 310 blades can be observed. This indicates pressure fluctuations and corresponding forces  
 311 acting on the liquid phase and gas phase. In addition, temporal fluctuations of the local  
 312 pressure field inside the chambers, which may lead to compression and decompression of  
 313 the gas pockets, is observed.

314 For quantitative analysis, the temporal gas holdup inside single chambers are calculated of  
 315 each reconstructed cross-sectional image for three different gas entrainments. Figure 11  
 316 shows the graphs of temporal progression of gas holdup inside a selected chamber. The  
 317 spatial distribution and development of the gas and liquid is visualized using tomographic  
 318 images that are assigned to the graphs and selected time steps. Considerable periodic gas  
 319 holdup fluctuations can be observed, especially for the case of gas entrainment of 0.03.  
 320 Here, the areas of gas and liquid are rapidly moving inside the chamber, which again trigger  
 321 the intensive phase interactions.





322

323 **Figure 11:** Gas holdup evolution inside a single chamber of the impeller for different gas flow rates  
 324 and corresponding tomographic images of selected states.

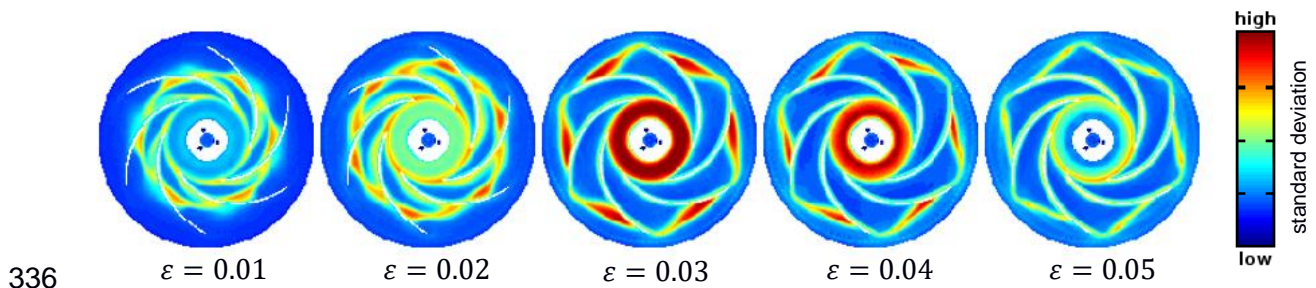
325

326 Eventually, the standard deviation

$$\sigma_{i,j} = \frac{1}{K-1} \cdot \sum_{k=1}^K (\alpha_{i,j,k} - \bar{\alpha}_{i,j})^2 \quad (6)$$

327 of the cross-sectional gas holdup can be used as a measure of the equiprobability of phases  
 328 in a volume element over time, which has been visualized in Figure 12 for various gas  
 329 entrainments. That is, it indicates areas with frequent phase transition. Such areas are  
 330 mainly found at the inlets of the chambers, the pressure sides of the blades or the wake of  
 331 the gas pockets. In contrast, a high stability of the gas pockets inside the chambers,

332 especially at the suction side of the blades, can be observed. Additionally, a very high  
333 interaction rate occurs in the area of the impeller eye at gas entrainments of  $\varepsilon = 0.03$  and  $\varepsilon =$   
334 0.04. This results from the large and unsteady gas agglomerations, which have been  
335 observed in the impeller eye and have been described before.



**Figure 12:** Visualization of the standard deviation of the cross-sectional gas holdup.

#### 339 4. Conclusion

340 In this paper, the capability of ultrafast X-ray computed tomography to disclose transient gas-  
341 liquid flow behavior within a centrifugal pump has been demonstrated. With the presented  
342 setup, cross-sectional gas phase distribution image sequences have been recorded for two  
343 general gas inlet conditions (disperse and swirling), three rotational speeds and inlet gas  
344 fraction in the range between 0.008 and 0.058. The fast imaging discloses the dynamics of  
345 even small flow structures very well. This includes gas bubbles of various size and thin liquid  
346 surges. Analysis of interfacial area and gas holdup variability showed, that gas-liquid  
347 interfaces in the impeller eye and in the chambers towards the outlet are highly agitated but  
348 also that the gas plugs in the chambers are very stable and hinder the transport of liquid. A  
349 more detailed analysis of this rich data is an upcoming task.

350

#### 351 Acknowledgment

352 The project was founded by the German Federal Ministry of Education and Research  
353 (BMBF) under the funding code 02NUK023B.

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