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Investigations on bubbly two-phase flow in a constricted vertical pipe

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Abstract

We report on an experimental investigation of adiabatic bubbly two-phase flow development in a DN50 pipe with a ring-shaped and a baffle-shaped constriction at different superficial velocities of gas (up to $j_g = 0.1400 \text{ m}\cdot\text{s}^{-1}$) and liquid (up to $j_l = 1.6110 \text{ m}\cdot\text{s}^{-1}$) using ultrafast electron beam X-ray computed tomography (UFXCT). From UFXCT images, cross-sectional gas holdup distributions were obtained with a temporal resolution of up to 2,500 frames per second in 18 scanning planes along the pipe. A sophisticated data processing approach was applied to extract gas holdup data immediately from the two-phase flow image stack. Based on that, time-averaged gas holdup of the cross-section and the axial center of the pipe were calculated. In addition, bubble sizes and velocities were determined.

Key words: gas-liquid two-phase flow, bubbly flow, flow constriction, three-dimensional flow, computed tomography, experimental benchmark data

25 **1 Introduction**

26 Two-phase flows can be found in many industrial applications. Examples are
27 multiphase chemical reactors, power plant circuits, heat exchangers or oil and gas
28 production. Hence, there is a continuing interest in modelling and simulation.
29 Computational fluid dynamics is the method of choice to simulate such flows at a
30 high level of detail. However, for two-phase flow such simulation codes are yet not
31 fully mature due to the inherent physical complexity of flows with phase
32 boundaries. This holds especially for gas-liquid two-phase flow due to the
33 deformability of gas-liquid interfaces. [1–3]. Thus, experimental validation is still
34 inevitable. The particular challenge there, however, is the need to produce data
35 with highest resolution in space and time, e.g. for transient flow phenomena.

36 Two phase flow in straight pipes of any inclination has been seen as a benchmark
37 case for multiphase CFD for some years now. Hence, numerous experimental test
38 cases are known from literature, e.g. for vertical upward flow [4–6], downward flow
39 [7–9] or both flow directions [10–12], as well as horizontal flow [13–15]. A logical
40 next step are benchmark cases for slightly more complex flow scenarios, such as
41 constrictions, bends or junctions, with significant three-dimensional flow effects,
42 such as flow separation at sharp edges, recirculation areas or curved streamlines.
43 For the latter, however, only very few CFD-grade experimental data are available.
44 One example is Prasser et al. [16] and Frank et al. [17], who investigated the flow
45 around an axially moveable semicircular obstacle for a vertical pipe with an inner
46 diameter of 195.3 mm using the wire-mesh sensor technique [18,19]. In these
47 studies, the authors measured phase distributions and bubble sizes with a
48 temporal resolution of 2,500 images per second for air-water and steam-water
49 flow. From this, axial and lateral gas bubble velocities as well as time-averaged
50 liquid velocities were estimated. The data was used for assessment and validation
51 of CFD simulations with ANSYS CFX employing a multiple size group modelling
52 approach for the gas phase [20]. The slight intrusiveness of the wire-mesh sensor

53 and the driving mechanism of the obstacle as well as the 3 mm spatial resolution
54 brought about increasing uncertainties for smaller bubbles and lower liquid
55 velocities [21,22]. The present study aimed at the extension of the available
56 experimental database for bubbly gas-liquid two-phase flow with a pronounced
57 three-dimensional flow field. Experiments have been performed in a vertical pipe
58 with an inner diameter of 53 mm. The impact of two different flow constrictions
59 on the flow field were studied: a baffle-shaped and a ring-shaped type,
60 respectively. The choice was made, because the baffle-shaped constriction creates
61 an asymmetric flow field while the ring-shaped one creates an axially symmetric
62 flow fields. This is useful to study different aspects of the flow, such as in-plane
63 flow components. Hence, some comparability to already existing experimental
64 data [16] is given for the baffle-shaped flow constriction. In addition, the ring-
65 shaped flow constriction provides a true extension of the available database.

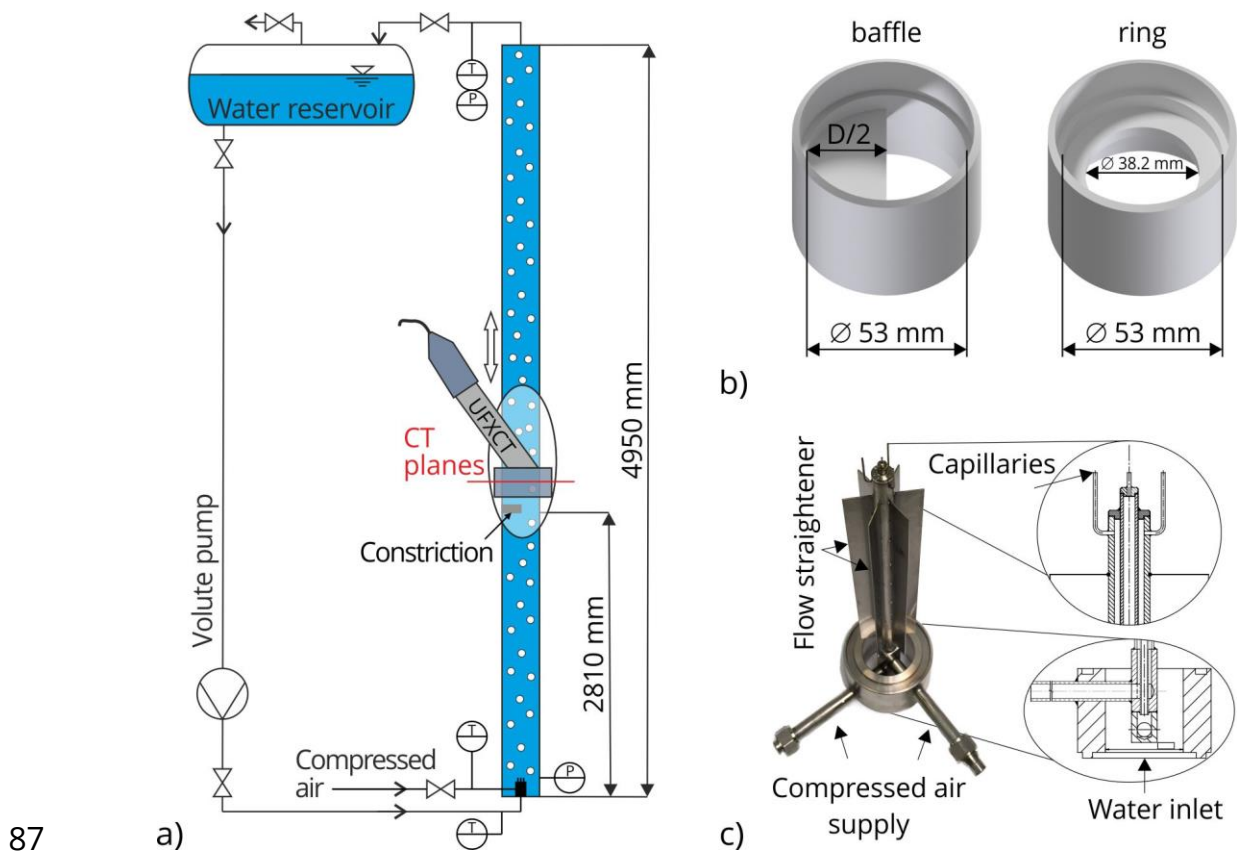
66 Experiments were performed using ultrafast X-ray computed tomography (UFXCT)
67 [23,24]. It is a fast and non-invasive imaging technique for the investigation of
68 highly transient processes, especially for bubbly two-phase flows [11,25–29]. With
69 the applied temporal resolution of up to 2,500 images per second, the fluid
70 dynamics could be studied without influencing the flow field. With this imaging
71 technique we obtained quantitative parameters, such as total phase holdups,
72 cross-sectional phase distributions, gas bubble sizes as well as their distributions
73 and velocities. In the following we discuss only selected results. For access to the
74 full data set the reader is referred to the RODARE Open Data Link given in [30,31].

75 **2 Experimental setup**

76 *2.1 Vertical test section*

77 Experiments are conducted in a vertical test section at the thermal-hydraulic test
78 facility TOPFLOW (see Figure 1 a)) [30], [31]. Here, flow investigations have been
79 performed under adiabatic conditions in an acrylic pipe with an inner diameter of

80 $D = 53$ mm and a total length of $L = 4950$ mm. Deionized water and compressed
 81 air were used as liquid and gas phase in co-current upward flow. Inlet flow rates
 82 are controlled by a volute pump (HPH 100-250, KSB, Germany) and a mass flow
 83 controller (F-202AC, Bronkhorst, Netherlands) for liquid and gas phase
 84 respectively. With this equipment we maintain a constant liquid temperature of
 85 30°C and pressure of 4 bar at the gas injection at the bottom of the test section.
 86



88 Figure 1: Schematic representations of the vertical obstructed test section showing a) the entire
 89 test section pipe connected to the (simplified and reduced depicted) TOPFLOW facility,
 90 b) the applied flow constrictions for generation of three-dimensional flow fields and c)
 91 the gas injection module.

92
 93 Figure 1 b) shows both flow constrictions, the baffle-shaped and ring-shaped one.
 94 Both block exactly half of the inner pipe cross-section. Each obstacle is 5 mm thick
 95 and its bottom edge is at a distance of $l = 2810$ mm above the gas injector. That is,

96 we have a length-to-diameter ratio of $l/D = 52$, for which we consider the two-
97 phase flow as fully developed.

98 Figure 1 c) shows the gas injection module that was already used in previous
99 studies, e.g. Banowski et al. for comparability study of UFXCT and wire-mesh
100 sensor technique [22]. It mainly comprises four capillaries with an inner diameter
101 of 0.8 mm and six equidistantly arranged metal sheets for straightening and
102 homogenizing the liquid flow.

103

104 2.2 *Ultrafast X-ray computed tomography*

105 Ultrafast electron beam X-ray computed tomography (UFXCT) uses a deflected
106 electron beam to produce a rapidly rotating X-ray spot. Along with a stationary
107 multi-pixel dual-plane X-ray detector this configuration is used to scan
108 tomographic projections of the flow. From these, cross-sectional images are
109 reconstructed. Each image has a size of 180×180 pixels with a corresponding pixel
110 size of 0.5 mm. The in-plane spatial resolution of the UFXCT scanner is nominally
111 1 mm. However, since gas-liquid flow has a specific contrast, we found in earlier
112 studies that detection of single gas bubbles is secure only for bubbles with a
113 diameter of $d_B \geq 2$ mm. The two imaging planes of the UFXCT scanner offer a
114 geometric distance of about 10 mm. The imaging speed in this study was up to
115 2,500 frames per second and per plane, depending on the expected flow velocity.
116 For more details on general principles of computed tomography, the reader is
117 referred to [34–36] and for more details on ultrafast X-ray computed tomography
118 to [24,37,38].

119 The UFXCT scanner can be freely moved along the pipe with the help of an elevator
120 mechanism. Hence it is possible to study the gas-liquid flow in any position up- and
121 downstream of the flow constriction. The scanning planes used in this study are

122 compiled in Table 1 as distances z of the upper and lower imaging plane with
 123 respect to the center of the flow constriction.

124

125 Table 1: Image plane identifiers along the vertical test section pipe and according distances z
 126 of the upper and lower UFXCT imaging plane to the center of the respective flow
 127 constriction. Additionally dimensionless distance-to-diameter ratios z/D are given.

Identifier	A	B	C	D	E	F	G	H	I
z [mm]	-200	-60	0	5	20	50	100	200	400
	-210	-70	-10	-5	10	40	90	190	390
z/D	-4	-1	0	0.1	0.5	1	2	4	8

128

129 2.3 Gas holdup

130 The raw tomographic data is a set of gray value images encoding the X-ray
 131 attenuation coefficient $\mu_{i,j,k}$ of a pixel with indices (i, j) and temporal index k . The
 132 conventional procedure to calculate gas holdup from UFXCT images is as follows:
 133 scans of the two-phase flow $\mu_{i,j,k}^{(tp)}$ and two k -averaged reference states, i.e. empty
 134 cross section $\bar{\mu}_{i,j}^{(gas)}$ and liquid filled cross section $\bar{\mu}_{i,j}^{(liq)}$, are used to calculate the
 135 gas holdup $\varepsilon_{i,j,k}$ according to

$$\varepsilon_{i,j,k} = \frac{\bar{\mu}_{i,j}^{(liq)} - \mu_{i,j,k}^{(tp)}}{\bar{\mu}_{i,j}^{(liq)} - \bar{\mu}_{i,j}^{(gas)}}. \quad (1)$$

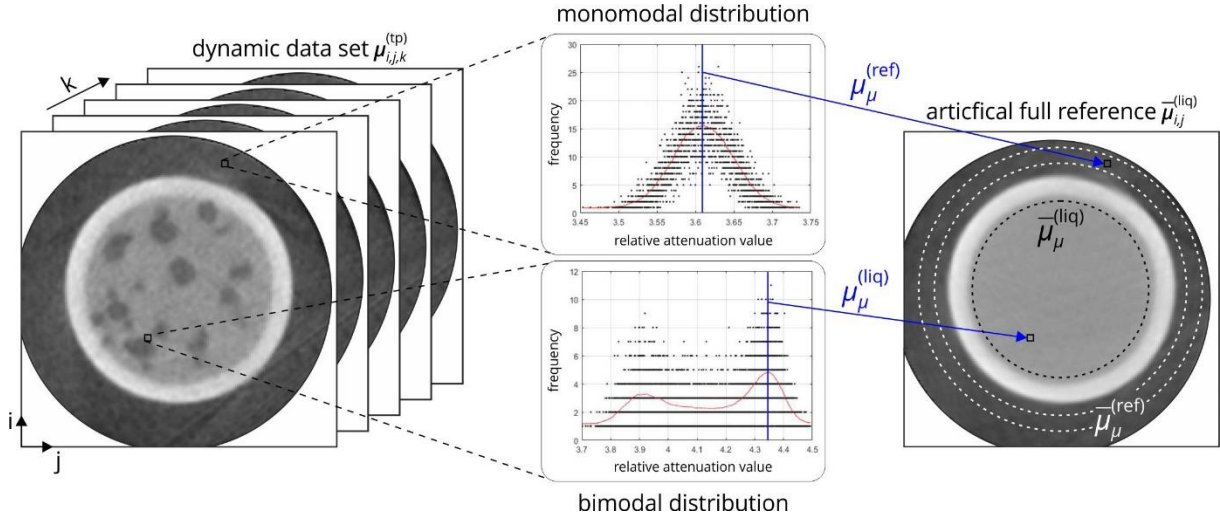
136 This method has already been introduced by Zalucky et al. [39]. However, it was
 137 found that this method is sensitive to image artifacts from e.g. beam hardening,
 138 radiation scattering and geometrical dispositions of the deflected X-ray source
 139 and/or the object of investigation [40].

140 Therefore, an improved data processing procedure was developed. Here, the
 141 liquid reference data set $\bar{\mu}_{i,j}^{(liq)}$ and an estimation of the attenuation difference

142 $\bar{\mu}_{i,j}^{(\text{liq})} - \bar{\mu}_{i,j}^{(\text{gas})}$ are directly extracted from the two-phase flow data $\mu_{i,j,k}^{(\text{tp})}$. The
143 calculation comprises two main processing steps: a) a histogram calibration step
144 from which the liquid reference data set $\bar{\mu}_{i,j}^{(\text{liq})}$ is obtained and b) an optimization
145 step from which the attenuation difference $\bar{\mu}_{i,j}^{(\text{liq})} - \bar{\mu}_{i,j}^{(\text{gas})}$ is estimated. This
146 approach effectively suppresses adverse effects of image artifacts and non-
147 linearities.

148 Figure 2 illustrates the first data processing step. Here, a histogram of all k
149 reconstructed attenuation values $\mu_{i,j,k}^{(\text{tp})}$ is compiled for each image pixel (i, j) . If the
150 average gas holdup of the corresponding pixel (i, j) is around 50%, then its
151 attenuation value distribution is typically bimodal (see Figure 2, bottom center).
152 Though the gas and liquid phase in a two-phase flow have well-defined
153 attenuation coefficients, the reconstructed values are corrupted by noise, artifacts
154 and non-linearities. As the Poisson noise of the X-ray source and the Gaussian
155 noise of the detectors are dominating we can assume a Gaussian distribution for
156 both values. Hence, we extract average liquid $\mu_{\mu}^{(\text{liq})}$ and gas $\mu_{\mu}^{(\text{gas})}$ values from $\mu_{i,j,k}^{(\text{tp})}$
157 by fitting two Gaussian curves into the histogram. This is done for all image pixels.
158 As the liquid phase is dominant in our case of bubbly two-phase flow, $\mu_{\mu}^{(\text{liq})}$ can be
159 determined with good accuracy. For $\mu_{\mu}^{(\text{gas})}$ it is more difficult, as its peak in the
160 histogram is typically weak or even missing. Note, if gas phase would be dominate,
161 e.g. for droplet flow, the situation would be vice versa.

162



163

164 Figure 2: Schematic illustration to extract a full reference data set $\bar{\mu}_{i,j}^{(liq)}$ from the dynamic two-
 165 phase flow data set $\mu_{i,j,k}^{(tp)}$ based on a frequency distribution analysis of attenuation
 166 values at each image pixel (i, j) .

167

168 Thus, the attenuation difference $\bar{\mu}_{i,j}^{(liq)} - \bar{\mu}_{i,j}^{(gas)}$ is determined in a second data
 169 processing step. As illustrated in Figure 2 we may obtain $\bar{\mu}_{i,j}^{(gas)}$ from reference
 170 pixels with average value $\bar{\mu}_{\mu}^{(ref)}$ outside the column. However, as it can also be seen
 171 in Figure 2, the gas values in the bubble are on average slightly brighter which is
 172 caused by partial volume effects as well as beam scattering and beam hardening
 173 artifacts. Therefore, the sought value $\bar{\mu}_{i,j}^{(gas)}$ is obtained in the following way.

174 We set $\bar{\mu}_{i,j}^{(gas)} = \bar{\mu}_{\mu}^{(ref)}$, calculate the gas holdup according to Eq. (1) and compile the
 175 histogram (left side of Figure 3). As can be seen, the gas holdup maximum is $\varepsilon < 1$
 176 while we would expect it to be $\varepsilon = 1$. Now, we fit a Gaussian distribution function
 177 to the right slope of the histogram and determine its mean value ε_m . Now the task
 178 is to find an appropriate average attenuation value for gas, which is larger than
 179 the reference value by an offset a , that is

$$\bar{\mu}_{i,j}^{(gas)} = \bar{\mu}_{\mu}^{(ref)} + a. \quad (2)$$

180 If this reference value shifts ε_m to 1, as we would expect, then Eq. (1) can be written
 181 as

$$\frac{\varepsilon_{i,j,k}}{\varepsilon_m} = \frac{1}{\varepsilon_m} \frac{\bar{\mu}_{i,j}^{(\text{liq})} - \mu_{i,j,k}^{(\text{tp})}}{\bar{\mu}_{i,j}^{(\text{liq})} - \bar{\mu}_\mu^{(\text{ref})}} = \frac{\bar{\mu}_{i,j}^{(\text{liq})} - \mu_{i,j,k}^{(\text{tp})}}{\bar{\mu}_{i,j}^{(\text{liq})} - (\bar{\mu}_\mu^{(\text{ref})} + a)} \quad (3)$$

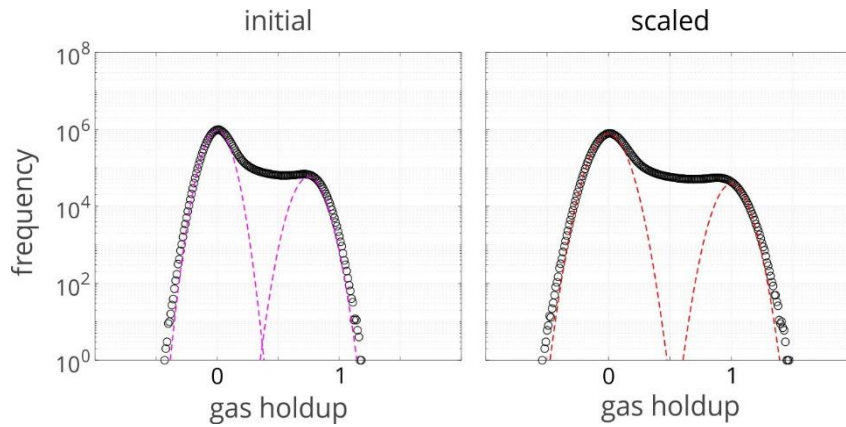
182 Setting $\Delta = \bar{\mu}_{i,j}^{(\text{liq})} - \bar{\mu}_\mu^{(\text{ref})}$ and solving for a yields

$$a = \Delta(1 - \varepsilon_m) \quad (4)$$

183 or by using Eq. (2)

$$\bar{\mu}_{i,j}^{(\text{gas})} = (1 - \varepsilon_m)\bar{\mu}_{i,j}^{(\text{liq})} + \varepsilon_m \bar{\mu}_\mu^{(\text{ref})}. \quad (5)$$

184 With this value for $\bar{\mu}_{i,j}^{(\text{gas})}$ we obtain the scaled histogram shown on the right side
185 of Figure 3.



186

187 Figure 3: Gas holdup histogram calculated according to Eq.(1) using $\bar{\mu}_\mu^{(\text{ref})}$ (left) and
188 $(1 - \varepsilon_m)\bar{\mu}_{i,j}^{(\text{liq})} + \varepsilon_m \bar{\mu}_\mu^{(\text{ref})}$ (right) as empty reference $\bar{\mu}_{i,j}^{(\text{gas})}$.

189

190 2.4 Gas phase parameters and bubble properties

191 From the $\varepsilon_{i,j,k}$ we can calculate the time-averaged cross-sectional gas phase
192 distribution:

$$\bar{\varepsilon}_{i,j} = \frac{1}{N_k} \sum_{k=1}^{N_k} \varepsilon_{i,j,k} \quad (6)$$

193 as well as time- and space-averaged total gas holdup

$$\bar{\varepsilon} = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} w_{i,j} \cdot \bar{\varepsilon}_{i,j}. \quad (7)$$

194 Here $w_{i,j}$ are weights encoding the fraction of pixel area inside the pipe cross
 195 section. In a next step, we binarize $\varepsilon_{i,j,k}$ in order to discriminate gas from liquid.
 196 Thus, an iterative algorithm is applied which is based on a concept proposed by
 197 Banowski et al. [41]. Here, pixel clusters are identified as connected objects based
 198 on seed points of maximum gas holdup. This algorithm finally yields two data sets:
 199 a) a binarized data set $\varepsilon_{i,j,k}^{(\text{bin})}$ containing values "1" and "0" for gas and liquid phase
 200 only and b) a corresponding identifier data set $\varepsilon_{i,j,k}^{(\text{id})}$ containing individual bubble
 201 numbers. Furthermore, the bubble property analysis module of the wire-mesh
 202 sensor data processing software is used to extract bubble properties, e.g. bubble
 203 size and its position [42].

204 In the image stack, the axial dimension is time k . Hence, the identified bubble
 205 volume is given in $\text{mm}^2 \cdot \text{ms}$. It is required to convert time into length measures,
 206 hence bubble volume needs to be multiplied by the axial gas phase velocity. To
 207 determine this velocity a cross-correlation function

$$F_{i,j,\Delta k} = \frac{\sum_{k=1}^{N_k} \varepsilon_{i,j,k}^{(\text{low})} \cdot \varepsilon_{i,j,k}^{(\text{up})}}{\sqrt{\sum_{k=1}^{N_k} \left(\varepsilon_{i,j,k}^{(\text{low})}\right)^2 \cdot \sum_{k=1}^{N_k} \left(\varepsilon_{i,j,k}^{(\text{up})}\right)^2}} \quad (8)$$

208 of the gas holdup is calculated for each pixel pair (i, j) of upper scanning plane
 209 $\varepsilon_{i,j,k}^{(\text{up})}$ and lower scanning plane $\varepsilon_{i,j,k}^{(\text{low})}$ separately. The index Δk corresponds to the
 210 time-shift $\Delta t = \Delta k / f$ with f being the image frequency per scanning plane. Then,
 211 the axial gas phase velocity map $\bar{u}_{i,j}^{(\text{ax})}$ is calculated using the maximum of the
 212 cross-correlation function according to

$$\bar{u}_{i,j}^{(ax)} = \frac{\Delta m_{i,j}}{\Delta k_{i,j}^{(max)}} \cdot f \quad \text{where} \quad \Delta k_{i,j}^{(max)} = \arg \max_k (F_{i,j,\Delta k}). \quad (9)$$

213 Here, the unequal distribution of the effective imaging plane distance of the UFXCT
 214 scanner is taken into account by the distance map $\Delta m_{i,j}$ as introduced by
 215 Neumann et al. [43]. This allows for a position-dependent calculation of bubble
 216 sizes. This approach is typically valid only for unidirectional flow, which is, however,
 217 not the case in areas around the flow constrictions and in recirculation zones.
 218 Here, morphological bubble properties are utilized to estimate the bubble velocity
 219 and, thus, the bubble size based on its Eötvös number and aspect ratio [11,22].
 220 Furthermore, the bubble size distribution is given by the frequency of occurrence
 221 of a respective size class according to

$$H^{(bub)}(d_{B,n}) = \frac{\sum_b \varepsilon(B_b)}{\bar{\varepsilon} \cdot \Delta d_B} \quad \text{with} \quad b \in \{1 \dots N_b \mid d(B_b) \in d_{B,n}\}. \quad (10)$$

222 Here, the frequency of occurrence $H^{(bub)}$ for bubble size class $d_{B,n}$ is defined as
 223 gas holdup ratio of the sum $\sum_b \varepsilon(B_b)$ and the time- and space-averaged gas
 224 holdup $\bar{\varepsilon}$, divided by bubble size class width Δd_B . The sum is given by each bubble
 225 B_b with b being element of the total bubble number N_b and the restriction that
 226 the bubble diameter of the respective bubble $d(B_b)$ belongs to bubble size class
 227 $d_{B,n}$. In addition, an alternative representation of the bubble size distribution is
 228 given by the probability density function (PDF) that is calculated by applying a
 229 kernel density estimation with an interval width of 10%.

230 Furthermore, redistribution of gas and liquid phase lead to significant lateral
 231 bubble movement, especially close to the flow constrictions. Therefore, the
 232 transversal movement of each bubbles center of mass is directly tracked for
 233 according cross-sectional images, which allows for the determination of its lateral
 234 velocity. Subsequently, the lateral velocity field $\bar{u}_{i,j}^{(lat)}$ is derived by void fraction

235 weighted time-averaging of the lateral velocity over each available bubble that
236 crossed the imaging plane during scanning [16].

237

238 **3 Results**

239 At the beginning of each experiment, deionized water is heated up and circulated
240 through the test section, using the volute pump. In parallel, the pressure is
241 increased by injecting de-oiled gas to the test section until both temperature and
242 pressure reaches stable conditions of 30°C and 4 bar respectively. Subsequently,
243 specific operating conditions are set by adjusting the liquid and gas flow rates as
244 defined by their respective superficial velocity (see Table 2). In total, fifteen steady
245 state operating conditions within the bubbly flow regime are considered for each
246 flow constriction, based on flow maps of Taitel et al. [44]. After a waiting period of
247 about 30 min the UFXCT scans are performed at the different scanning heights,
248 starting at position “A” (see Table 1), for a scanning interval of 15 s. The imaging
249 frequency has been adapted corresponding to the expected flow velocity within
250 the pipe (see Table 2) to obtain a sufficient number of images.

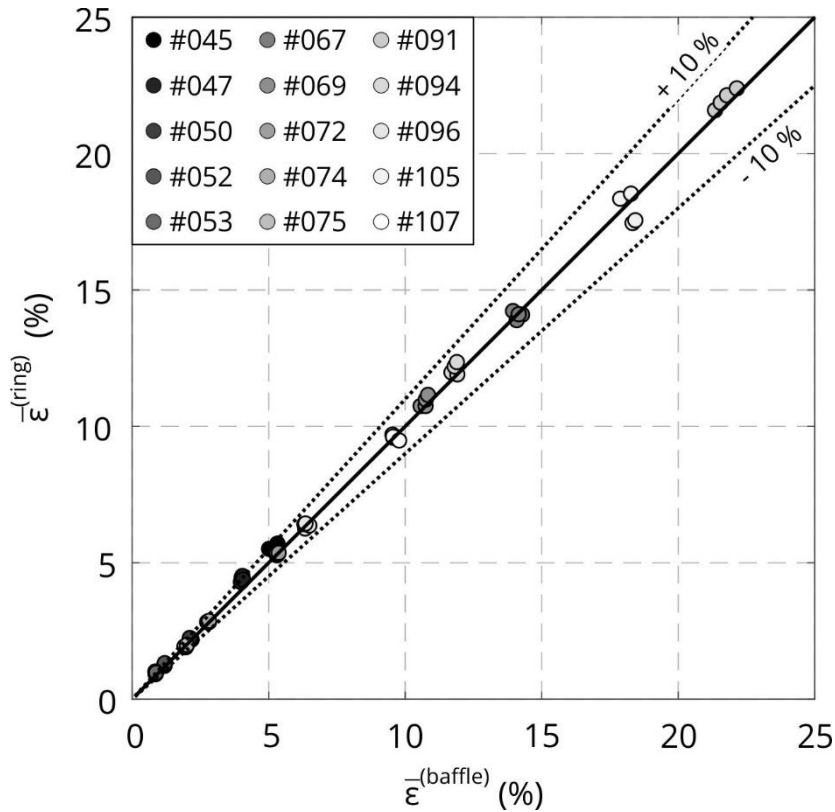
251

252 Table 2: Experimental matrix for both flow constrictions based on various combinations of gas
 253 and liquid superficial velocities. Highlighted numbers identify the applied UFXCT image
 254 frequency f per scanning plane (blue: 1,000 Hz; green: 2,500 Hz).

		j_g – gas superficial velocity				
		$m \cdot s^{-1}$	0.0151	0.0368	0.0898	0.1400
j_l – liquid superficial velocity	1.6110	#053	#075	-	-	
	1.0170	#052	#074	#096	#107	
	0.4050	#050	#072	#094	#105	
	0.1020	#047	#069	#091	-	
	0.0405	#045	#067	-	-	

255

256 As a first analyzing step, the initial flow conditions for each flow constrictions and
 257 operating condition are compared. Therefore, the total gas holdup values $\bar{\epsilon}$ of the
 258 four furthest upstream imaging planes (upper and lower UFXCT imaging plane for
 259 scanning positions “A” and “B”) are compared as the two-phase flow is here
 260 undisturbed and fully developed. The corresponding parity plot in Figure 4 shows
 261 deviations of $\bar{\epsilon}$ smaller than $\pm 10\%$.



262

263 Figure 4: Parity plot of total gas holdup $\bar{\epsilon}$ values of the undisturbed two-phase flow at the
 264 furthest upstream imaging planes of both flow constrictions.

265

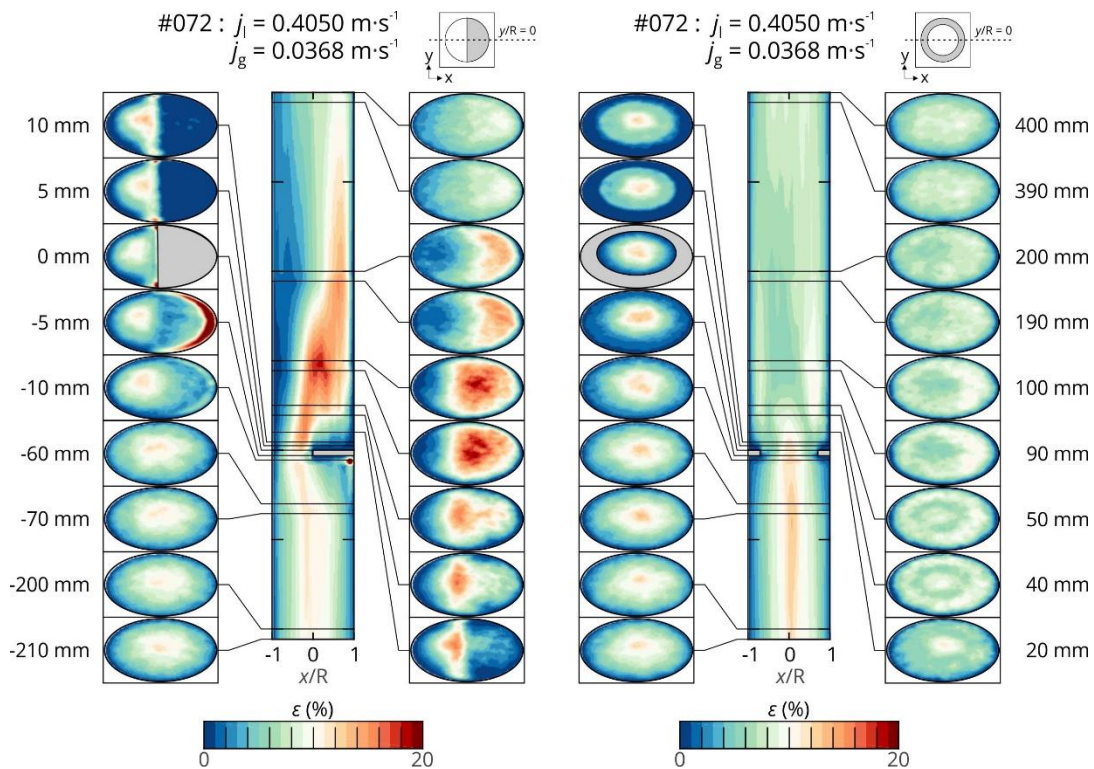
266 The coefficient of variation reveals a maximum deviation value of 7.16% for the
 267 lowest gas holdups. This proves undisturbed two-phase flow conditions upstream
 268 of the flow constrictions for each operating point, which is an important quality
 269 criterion for CFD comparison and allows for the characterization of the flow
 270 constriction impact on the flow field excluding operational influences.
 271 Furthermore, the result of the initial flow condition comparison proves the
 272 reliability of the introduced image data processing procedure.

273

274 3.1 Gas holdup and phase distribution

275 Figure 5 exemplarily shows sectional views of the gas fraction through the
 276 cross-sectional center of the test section pipe ($-1 \leq x/R \leq 1$ for $y/R = 0$) for both
 277 flow constrictions and superficial velocities of $j_1 = 0.4050 \text{ m}\cdot\text{s}^{-1}$ and $j_g = 0.0368 \text{ m}\cdot\text{s}^{-1}$

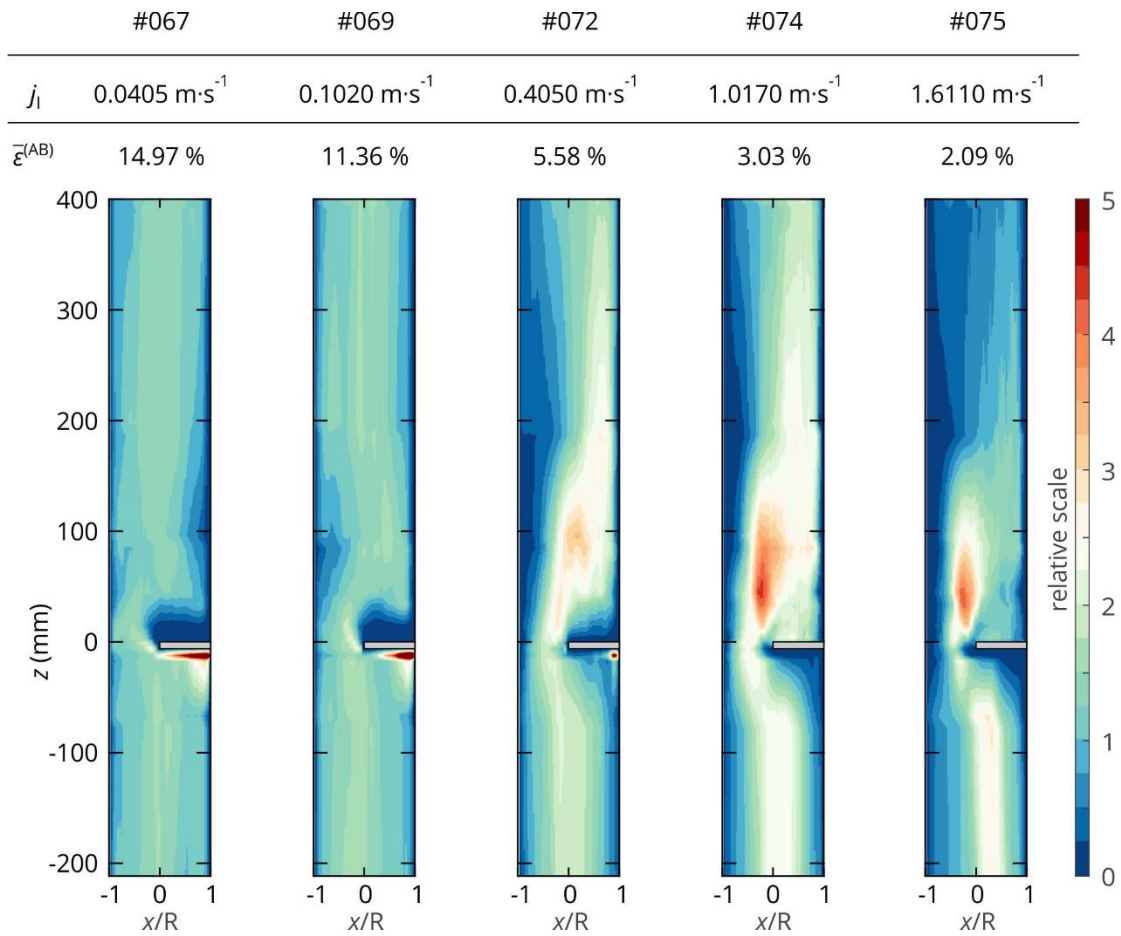
278 (#072). In addition, the time-averaged cross-sectional gas fractions $\bar{\varepsilon}_{i,j}$ are shown.
 279 The sectional views are perpendicularly arranged to the edge of the baffle-shaped
 280 flow constriction and show the linearly interpolated time-averaged gas holdup
 281 values obtained at the 18 imaging planes. Such sectional views allow a comparison
 282 of both flow constrictions, showing gas accumulations for wide areas of the pipe,
 283 especially downstream of the baffle-shaped flow constriction. In contrast, gas is
 284 clearly redistributed while passing the blockage, leading to a homogenization of
 285 the gas phase distribution far downstream of the flow constriction in case of the
 286 ring-shaped type.



287
 288 Figure 5: Time-averaged gas fraction sectional views up- and downstream of the baffle-shaped
 289 (left) and ring-shaped (right) flow constriction.

290
 291 Another visualization of determined gas holdup values $\bar{\varepsilon}_{i,j}$ is given in Figure 6.
 292 Here, each of the sectional views are additionally normalized to its corresponding
 293 averaged total gas holdup $\bar{\varepsilon}^{(AB)}$ of imaging planes "A" and "B" that is also indicated
 294 at the top of Figure 6. Thus, the color scaling can be interpreted as the relative

295 amount of gas phase that is distributed along the test section pipe compared to
 296 unaffected flow conditions. Hence, this kind of visualization allows detailed
 297 investigations on various operating conditions for a given flow constriction. In
 298 Figure 6 results for constant gas superficial velocity of $j_g = 0.0368 \text{ m}\cdot\text{s}^{-1}$ and
 299 increasing liquid superficial velocities for the baffle-shaped flow constriction are
 300 shown.



301
 302 Figure 6: Time-averaged and normalized gas holdup values $\bar{\epsilon}_{i,j}/\bar{\epsilon}^{(AB)}$ up- and downstream of the
 303 baffle-shaped flow constriction for various superficial liquid velocities j_l and a constant
 304 superficial gas velocity of $j_g = 0.0368 \text{ m}\cdot\text{s}^{-1}$.

305
 306 It can be concluded that all operating conditions provide symmetric flow profiles
 307 for the unaffected region upstream of the flow constriction for $z < -60 \text{ mm}$ with a
 308 maximum at the pipe center. After that, the influence of the half-sided blockage
 309 on the phase distribution becomes more and more evident and leads to gas

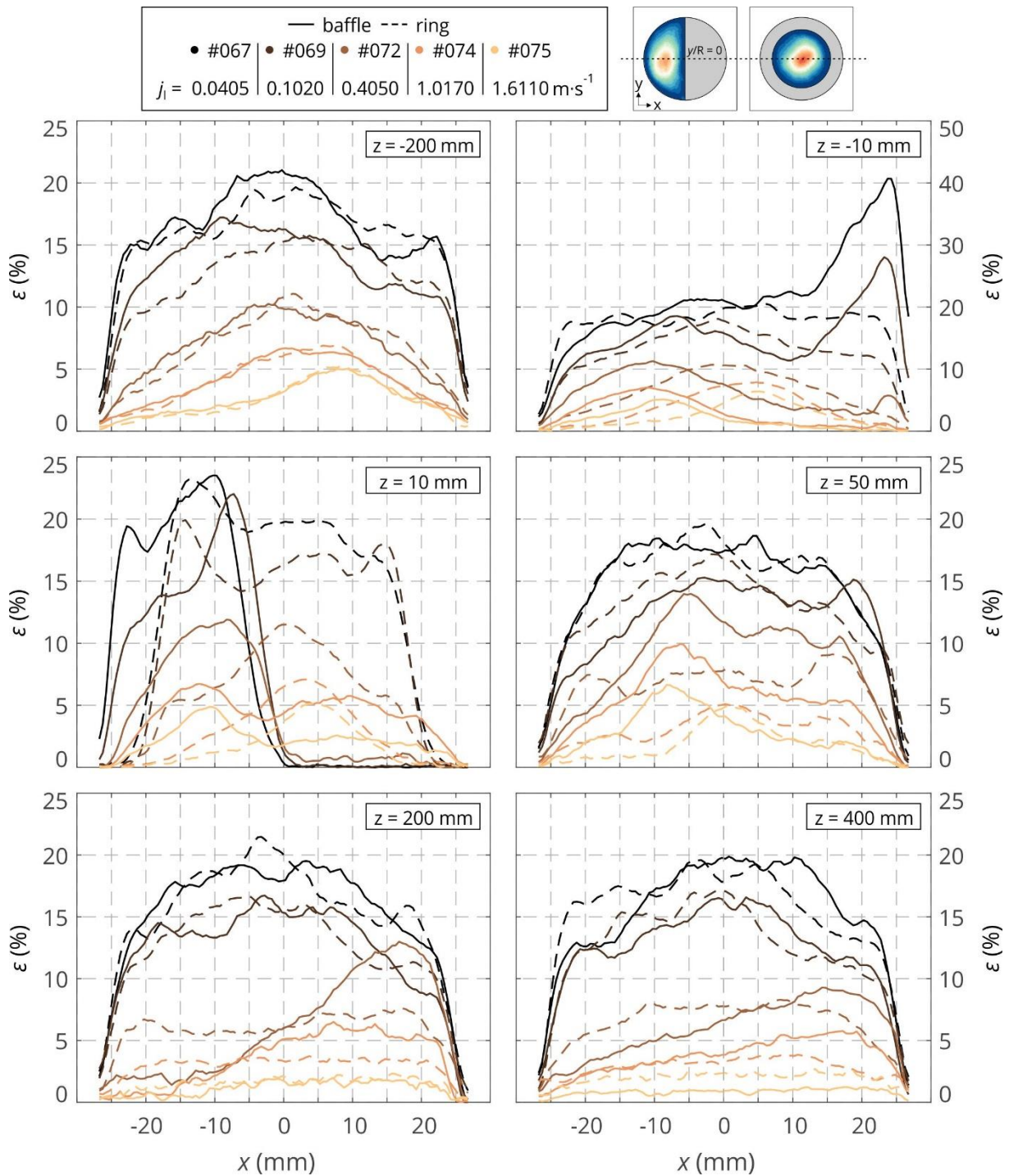
310 accumulations below the flow constriction for the two lowest superficial liquid
311 velocities (#067, #069) since the redirected liquid flow does not provide enough
312 energy to directly transport the gas phase towards the unobstructed side of the
313 pipe. With increasing superficial liquid velocity the gas accumulation below the
314 flow constriction decreases until it is completely vanished for $j_l \geq 1.0170 \text{ m}\cdot\text{s}^{-1}$
315 (#072).

316 In contrast, gas is accumulated directly downstream of the flow constriction for
317 higher superficial liquid velocities (#072, #074 and #075). This clearly indicates the
318 presence of a recirculation area above the flow constriction that is caused by the
319 strong flow separation at the edge of the flow constriction. For highest superficial
320 liquid velocity $j_l = 1.6110 \text{ m}\cdot\text{s}^{-1}$ (#075) a large amount of gas accumulates straight
321 above the edge of the flow constriction, which indicates that the momentum of
322 the recirculated liquid is even high enough to displace gas from the recirculation
323 area back to the pipe center. However, no significant recirculating zone is found
324 for the two lowest superficial liquid velocities (#067, #069). Here, the flow almost
325 immediately re-develops to undisturbed pipe flow conditions, whereas significant
326 asymmetric flow fields are found far downstream of the flow constriction for all
327 other operating conditions (#072, #074 and #075). For the latter, gas is clearly
328 redistributed to the obstructed side of the pipe, which is caused by the lower
329 density of gas that is driven out of the accelerated liquid jet.

330 A more quantitative comparison is shown in Figure 7, where selected gas holdup
331 profiles from representative imaging planes up- and downstream of both flow
332 constrictions are plotted for the same operating conditions as already depicted in
333 Figure 6. For $z = -200 \text{ mm}$ the comparison of both flow constrictions show similar
334 holdup profiles for all operating conditions, although the overall amount of gas
335 decreases for increasing liquid superficial velocity.

336 Directly upstream of the baffle-shaped flow constriction at $z = -10 \text{ mm}$ a gas
337 accumulation zone with approximately twice as much gas as at the unobstructed

338 pipe section is found below the blockage for operating conditions #067 and #069.
339 In contrast, almost no gas is found in this area for all other operating conditions.
340 Here, gas is clearly redistributed to the unobstructed pipe section, where a center
341 peak is developed at $x \approx -10$ mm. However, no significant stagnation zones or gas
342 redistribution are found for the ring-shaped flow constriction. Considering the
343 higher flow velocity due to the acceleration, the gas holdup is expected to decrease
344 close to the ring-shaped flow constriction. However, the profiles provide nearly the
345 same holdup maxima as for $z = -200$ mm (by respecting the different scaling).
346 Thus, it can be derived that gas is redistributed to the pipe center, where the
347 superimposition of the acceleration and redistribution effect result in
348 approximately constant gas holdup profiles along the centerline of the pipe.



349

350 Figure 7: Gas holdup profiles for selected imaging planes up- and downstream of each flow
 351 constriction for operating points #067, #069, #072, #074 and #075, showing the effect
 352 of increasing liquid superficial velocity j_l .

353

354 In the near vicinity downstream of the flow constriction at $z = 10$ mm gas is clearly
 355 redistributed towards the unobstructed pipe section for $j_l \leq 1.0170$ m·s⁻¹ and
 356 baffle-shaped flow constriction. In contrast, the gas holdup profiles show an

357 additional plateau for higher liquid superficial velocities (#074 and #075), due to
358 the recirculating flow in this area. Furthermore, the maxima of the profiles are
359 slightly eccentric towards the edge of the flow constriction with regard to the
360 unobstructed pipe section. In case of the ring-shaped flow constriction the holdup
361 profiles provide a more narrow distribution of the gas in the pipe center as
362 compared to the upstream condition. Here, the expansion of the flow leads to
363 significant lateral movement of the liquid, which in turn drives the gas towards the
364 pipe center due to its lower density.

365 At $z = 50$ mm, the flow re-develops for operating conditions #067 and #069,
366 independent of the flow constriction. On the other hand, the recirculating flow
367 causes a maximum of the holdup profiles between $-8 \text{ mm} \leq x \leq -5 \text{ mm}$ for higher
368 liquid superficial velocities (#072, #074 and #075) in case of the baffle-shaped flow
369 constriction. In contrast, not only a center peak, but also two peaks near the pipe
370 wall are found in cases of the ring-shaped flow constriction for operating
371 conditions #072 and #074. The latter are caused by recirculating flow in the wake
372 region of the flow constriction. However, this recirculation is less pronounced than
373 for baffle-shaped type and is furthermore not noticeable for operating point #075.

374 Further downstream at $z = 200$ mm and $z = 400$ mm the gas holdup profiles
375 indicate that the two-phase flow is fully re-developed for operating conditions
376 #067 and #069 for both flow constrictions and no significant redistributions of the
377 gas are noticeable compared to the unaffected upstream conditions. In contrast,
378 the flow seems to be also re-developed for higher liquid superficial velocities
379 (#072, #074 and #075) and the ring-shaped flow constriction, but with a persisting
380 difference in the gas distribution, since no significant peaks are found as in case
381 of unaffected upstream conditions. On the other hand, a clear redistribution of
382 the gas towards the obstructed side of the pipe cross-section is still present for
383 those liquid superficial velocities in case of baffle-shaped flow constriction.

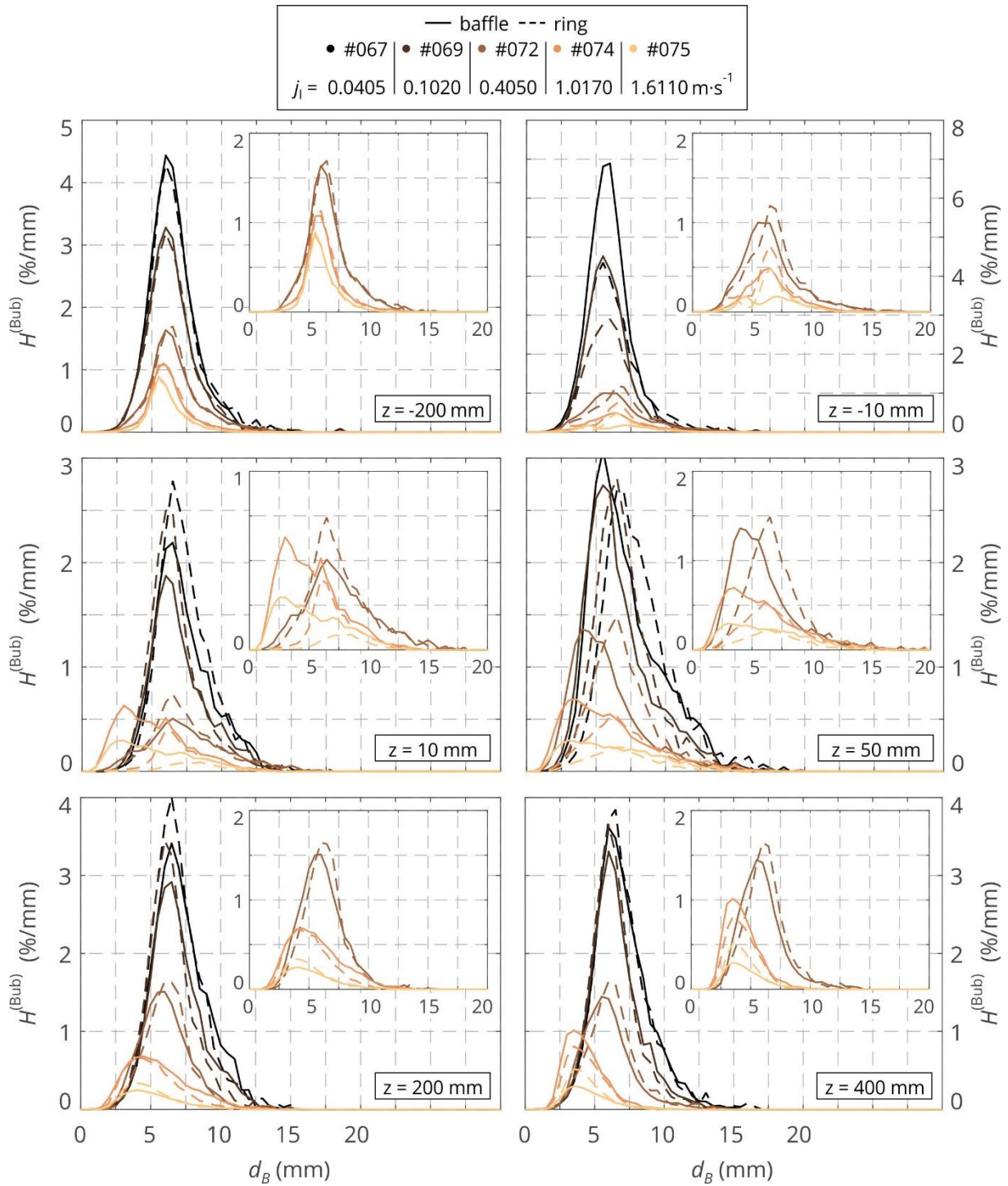
384 Although the peaks decay for increasing relative distances, the flow requires
385 longer distances to re-develop for these operating conditions.

386

387 3.2 *Bubble sizes*

388 The impact of both, baffle-shaped and ring-shaped flow constriction, on bubble
389 sizes and their distribution is shown in Figure 8 for a bubble size class width of
390 $\Delta d_B = 0.5$ mm, again for the same operating conditions and imaging planes as
391 described in Figure 6. For better visual interpretation of the results, the bubble size
392 distributions of operating conditions #072, #074 and #075 are additionally shown
393 in the rescaled inset plots. A comparison of the undisturbed two-phase flow at
394 relative distance $z = -200$ mm reveals no change of the bubble size distribution for
395 both investigated flow constrictions. A most probable bubble diameter of
396 $d_B \approx 6.0$ mm can be identified for all cases, which was already observed by
397 Banowski et al. [22]. Thus, on the one hand it can be assumed that the gas injector
398 produces bubbles of comparable size over a wide range of inlet conditions and,
399 on the other hand, that the flow is fully developed for all considered operating
400 conditions. However, even smaller bubbles might be expected for highest liquid
401 superficial velocities, where higher shear forces and thus higher bubble break-up
402 is expected. In the near vicinity upstream of the flow blockage at $z = -10$ mm the
403 bubble size distribution is similar to the undisturbed upstream flow condition for
404 operating conditions #067, #069 and #072 for both flow constrictions. Slightly
405 larger bubbles are found for operating point #074 and both flow constrictions, as
406 well as operating point #075 in case of the rings-shaped flow constriction. Here,
407 the sudden reduction of the test section pipe leads to increased lateral movement
408 of the two-phase flow and, thus, a redistribution of the gas towards the unblocked
409 pipe cross-section or pipe center in case of baffle-shaped or ring-shaped flow
410 constriction respectively. Thus, bubble coalescence becomes more probable. In
411 contrast, two peaks of the bubble size distribution are found for operating point

412 #075 and baffle-shaped flow constriction. Here, the liquid velocity gradients cause
413 high shear forces that additionally split bubbles. The superposition of both effects,
414 break-up and coalescence respectively, lead to most probable bubble sizes of
415 4.5 mm and 7.0 mm.



416

417 Figure 8: Bubble size distribution as frequency of occurrence $H^{(Bub)}$ for selected imaging planes
 418 up- and downstream of each flow constriction for operating points #067, #069, #072,
 419 #074 and #075, showing the effect of increasing liquid superficial velocity j_l . For better
 420 visual interpretation, insets represent a close-up view of operating points #072, #074
 421 and #075.

422

423 Directly downstream of the flow constriction at $z = 10$ mm, the bubble size
 424 distribution for operating conditions #067, #069 and #072 shows no significant

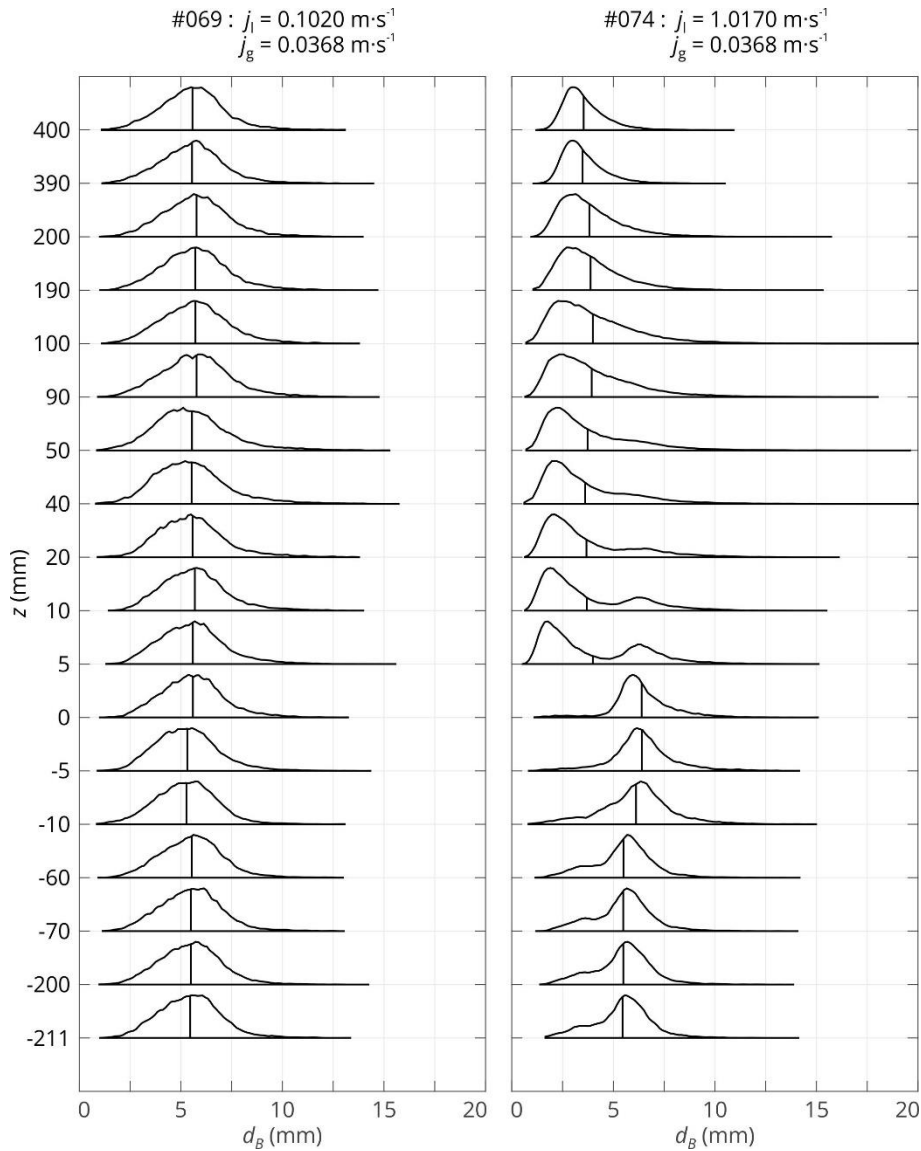
425 difference as compared to the undisturbed flow for both flow constrictions.
426 However, slightly higher amount of bubbles with $d_B \leq 4.0$ mm are found in case
427 of baffle-shaped flow constriction and at operating point #072, which are caused
428 by the higher shear of the accelerated flow. Furthermore, the bubble size
429 distribution provides a peak at smaller bubbles of $d_B \approx 3.0$ mm and also a wider
430 distribution for operating conditions #074 and #075 in case of baffle-shaped flow
431 constriction. In contrast, less but larger bubbles are found for the same operating
432 conditions and ring-shaped flow constriction. Thus, the symmetric reduction of the
433 cross-section causes less break-up of bubbles but higher coalescence rates at this
434 relative distance to the flow constriction.

435 At $z = 50$ mm, the recirculation of the flow causes a wider distribution of the
436 bubble sizes, as well as a most probable bubble size of 4.0 mm, 3.5 mm and
437 3.0 mm for baffle-shaped flow constriction and operating conditions #072, #074
438 and #075, respectively. This is an explicit indicator for the complex interaction of
439 break-up and coalescence effects in the recirculation area in the wake of the
440 baffle-shaped flow constriction. Furthermore, the bubble size distribution is
441 slightly shifted towards smaller bubbles for the same three operating conditions
442 in case of the ring-shaped flow constriction, since gas is already redistributed
443 towards the pipe wall and, thus, more bubble break-up occurs. In contrast,
444 operating conditions #067 and #069 show slightly higher amounts of larger
445 bubbles with $d_B = 8.0 \dots 14.0$ mm for both flow constrictions. Further downstream
446 of the flow constriction ($z = 200$ mm and 400 mm) the bubble size distribution
447 shows no significant changes but a slight increase of larger bubbles for operating
448 conditions #067 and #069 due to the reduced static pressure within the test
449 section. Furthermore, the bubble size distribution for operating point #072 is
450 approximately equal to the undisturbed upstream flow but with slightly smaller
451 most probable bubble size of $d_B \approx 5.5$ mm, also for both flow constrictions. Thus,
452 in terms of bubble sizes the two-phase flow has already re-developed at

453 $z = 200$ mm, although the gas is still redistributed as shown in Figure 7. In contrast,
454 bubble sizes are further decreased, resulting in a left skewed distribution for
455 operating conditions #074 and #075 in case of both flow constrictions. Here, the
456 high shear forces are still producing higher break-up rates of the bubbles and the
457 flow has not yet reached stable flow conditions.

458 In Figure 9 the bubble size distribution is shown as probability density function
459 (PDF) for all imaging planes and operating points #069 and #074. It shows the
460 development of the bubble size distribution up- and downstream of the
461 baffle-shaped flow constriction. Additionally, the averaged bubble diameter \bar{d}_B is
462 indicated as black vertical line for each distribution. In case of operating point
463 #069, no significant changes of the shape of the bubble size distribution as well as
464 the mean bubble diameter is discovered over the entire test section, which is
465 similar to results of the frequency of occurrence presented in Figure 8. In contrast,
466 a clear impact of the baffle-shaped flow constriction on the bubble size
467 distribution is found for operating point #074. On the one hand, the averaged
468 bubble diameter \bar{d}_B clearly decreases downstream of the flow constriction,
469 verifying the increased bubble break-up also in terms of the PDF. On the other
470 hand, the change of shape from mono- to bi-modal distribution (and vice-versa) of
471 the bubble size in the recirculation zone behind the flow constriction is clearly
472 provable ($z = 5...50$ mm). Subsequently, bubble sizes of operating point #074 show
473 narrower distributions as compared to operating point #069 for unaffected
474 upstream as well as far downstream flow conditions.

475



476

477 Figure 9: Bubble size distribution as probability density function for all imaging planes up- and
 478 downstream of the baffle-shaped flow constriction and operating points #069 and
 479 #074.

480

481 In Table 3, mean bubble diameters for undisturbed flow $\bar{d}_B^{(in)}$ and affected flow
 482 $\bar{d}_B^{(out)}$ for both flow constrictions are shown for the same operating conditions as
 483 in Figure 8. Here, $\bar{d}_B^{(in)}$ and $\bar{d}_B^{(out)}$ represent the averaged mean diameter of the four
 484 upstream imaging planes of scanning positions "A", "B" and of the two downstream
 485 imaging planes of scanning position "I", respectively. Eventually, the change in
 486 mean bubble size is defined as $\bar{d}_B^{(ratio)} = \bar{d}_B^{(out)} / \bar{d}_B^{(in)}$. It can be seen, that $\bar{d}_B^{(in)}$ is
 487 approximately equal for all operating conditions, whereas $\bar{d}_B^{(out)}$ clearly decreases

488 with increasing liquid superficial velocity. No influence of the flow constriction is
 489 recognizable for operating condition #067, where the mean bubble size increases
 490 because of the decreased static pressure within the test section. Interestingly, the
 491 mean bubble diameter is influenced in the same way for both flow constrictions,
 492 despite the different bubble size distributions as discussed for Figure 8.

493

494 Table 3: Mean bubble diameter \bar{d}_B for operating points #067, #069, #072, #074 and #075,
 495 showing the effect of increasing liquid superficial velocity j_l . The listed values represent
 496 averaged data for undisturbed flow upstream $\bar{d}_B^{(in)}$ and affected flow downstream
 497 $\bar{d}_B^{(out)}$ of each flow constriction, as well as their ratio $\bar{d}_B^{(ratio)}$.

	baffle-shaped constriction					ring-shaped constriction				
	#067	#069	#072	#074	#075	#067	#069	#072	#074	#075
$\bar{d}_B^{(in)}$	5.68	5.50	5.59	5.49	5.69	5.69	5.54	5.68	5.51	5.69
$\bar{d}_B^{(out)}$	5.83	5.57	4.96	3.52	3.60	5.88	5.58	5.27	3.65	3.72
$\bar{d}_B^{(ratio)}$	1.03	1.01	0.89	0.64	0.63	1.03	1.01	0.93	0.66	0.65

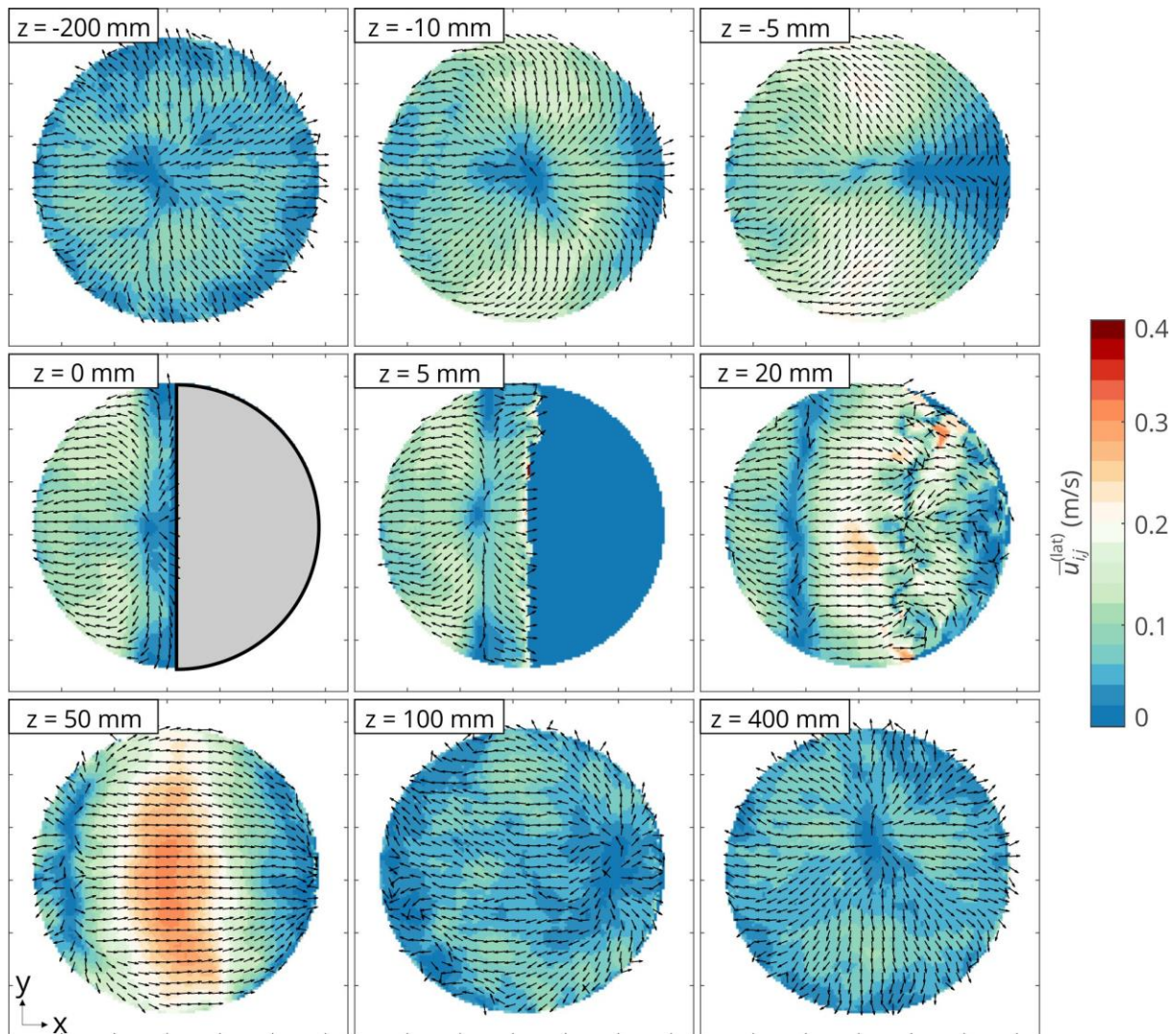
498

499 3.3 Lateral bubble velocities

500 In the following, calculated lateral bubble velocity fields for selected imaging
 501 planes up- and downstream of the baffle-shaped flow constriction are discussed
 502 for operating conditions #069 (Figure 10) and #074 (Figure 11). Both operating
 503 conditions represent two main distinct flow fields that are found in all investigated
 504 operating conditions: a) flow fields with gas accumulation upstream of the
 505 baffle-shaped flow constriction, but nearly no recirculating flow downstream of it
 506 and b) a strong recirculating flow in the wake of the flow constriction for higher
 507 liquid superficial velocities. For better visualization, the magnitude of lateral
 508 bubble velocity is given by colored image plots, whereas the direction is given by
 509 normalized velocity vectors.

510 In Figure 10 the lateral bubble velocity field of operating point #069 with lower
511 liquid superficial velocity of $j_l = 0.1020 \text{ m}\cdot\text{s}^{-1}$ is shown. In case of unaffected
512 two-phase flow at maximum distance upstream of the baffle-shaped flow
513 constriction only low lateral bubble velocity and, thus, lateral movement of the
514 bubbles is found. The velocity vectors point mainly outwards from the center of
515 the pipe because the lateral movement is dominated by bubbles with
516 $d_B < 5.5 \text{ mm}$, which move towards the pipe wall due to the lift force. The lateral
517 movement clearly increases in the direct vicinity upstream of the flow constriction
518 at $z = -10 \text{ mm}$. Here, both radial and azimuthal bubble movement is found, which
519 appears to be counteractive regarding the center plane of the pipe that is
520 perpendicular to the edge of the flow constriction. Following the flow progress, at
521 $z = -6 \text{ mm}$, bubbles mainly move towards the unobstructed pipe section which is
522 also found at the center height of the flow constriction. After passing the flow
523 constriction, two distinct zones with approximately equal lateral bubble velocity
524 are found. The velocity vectors show both movement towards the unobstructed
525 and the obstructed pipe section. Interestingly, both zones are separated by a
526 defined line of zero bubble velocity, which moves from the edge of the flow
527 constriction towards the periphery of the unobstructed pipe section from at
528 $z = 0 \text{ mm}$ to 50 mm , respectively. In this course, bubble movement towards the
529 obstructed pipe section becomes more dominant with a clear maximum at
530 $z = 50 \text{ mm}$. Further downstream, the lateral bubble velocity field shows again
531 unaffected behavior in terms of velocity magnitude and vectors.

532



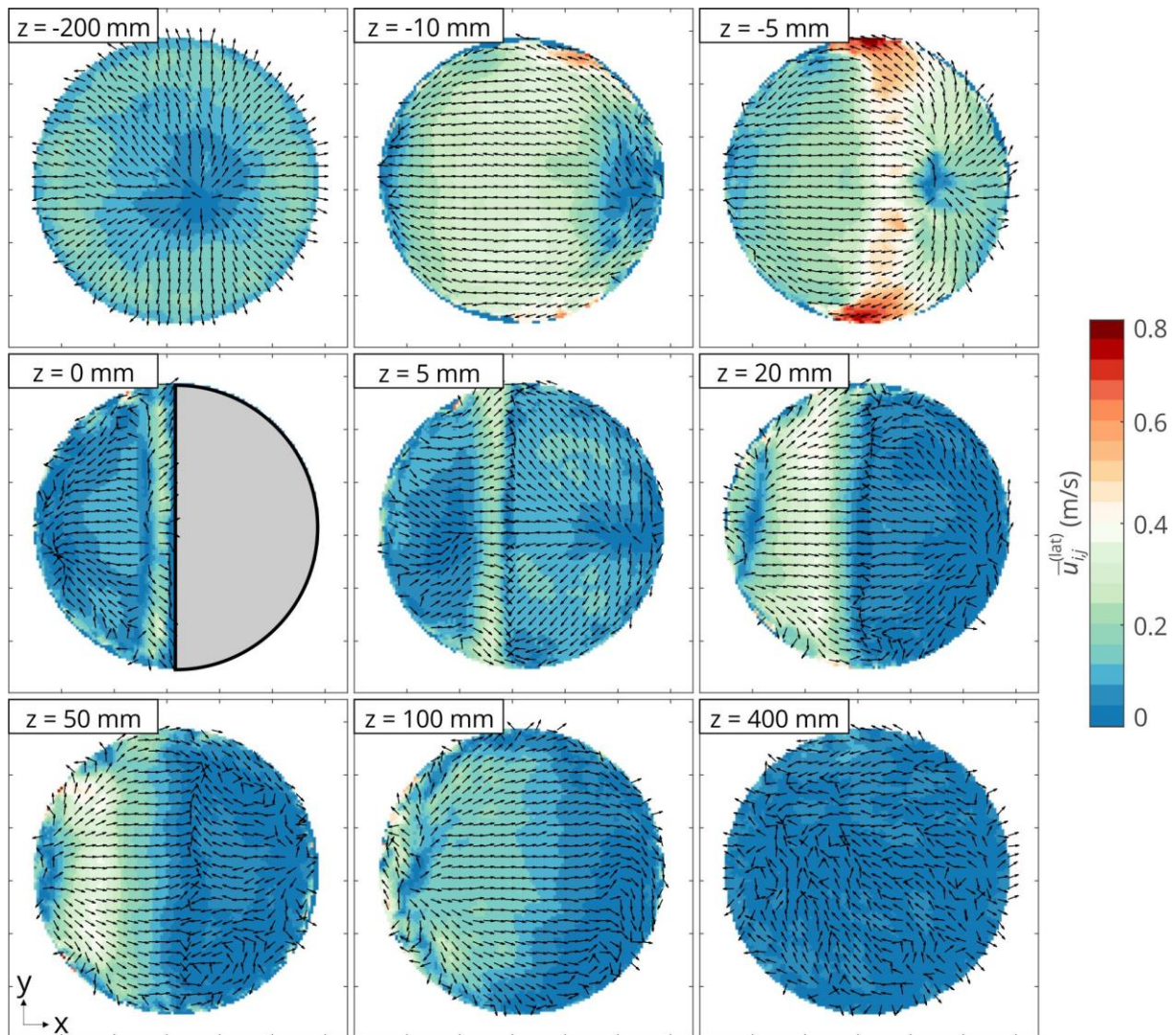
533

534 Figure 10: Lateral bubble velocity fields for selected imaging planes up- and downstream of the
 535 baffle-shaped flow constriction for operating point #069 with $j_l = 0.1020 \text{ m}\cdot\text{s}^{-1}$ and
 536 $j_g = 0.0368 \text{ m}\cdot\text{s}^{-1}$. The color scaling shows the magnitude and the arrows show the
 537 velocity vectors of the lateral bubble velocity (velocity vectors are normalized for better
 538 visualization).

539

540 In contrast, Figure 11 shows lateral bubble velocity fields for operating point #074
 541 with higher liquid superficial velocity of $j_l = 1.0170 \text{ m}\cdot\text{s}^{-1}$. Although the lateral
 542 bubble velocity is higher for unaffected two-phase flow at maximum distance to
 543 the flow constriction, the direction of the velocity vectors is comparable to
 544 operating point #069. However, the liquid velocity gradient between center and
 545 wall region is steeper whereby the lateral bubble velocities rise correspondingly.
 546 Close to the flow constriction, the lateral movement clearly increases again.

547 However, in contrast to operating point #069 velocity vectors mainly point towards
 548 the unobstructed pipe section with less azimuthal movement.



549
 550 Figure 11: Lateral bubble velocity fields for selected imaging planes up- and downstream of the
 551 baffle shaped flow constriction for operating point #074 with $j_l = 1.0170 \text{ m}\cdot\text{s}^{-1}$ and
 552 $j_g = 0.0368 \text{ m}\cdot\text{s}^{-1}$. The color scaling shows the magnitude and the arrows show the
 553 velocity vectors of the lateral bubble velocity (velocity vectors are normalized for better
 554 visualization).

555
 556 By passing the flow constriction at $z = 0 \text{ mm}$, only low lateral movement is found
 557 and bubbles tend to move to the edge of the flow constriction.
 558 In the following downstream wake region from $z = 0 \text{ mm}$ to 50 mm recirculating
 559 flow with negative axial liquid velocity is found at the obstructed pipe section. This
 560 velocity is, however, lower than for the unobstructed pipe section, which forces

561 bubbles mainly towards the centerline of the pipe straight above the edge of the
562 flow constriction. In contrast, nearly no lateral movement is found in the
563 downward flow, especially at $z = 20$ mm and 50 mm, and the bubble velocity
564 vectors indicate only statistical fluctuations, and, thus, no clear directed
565 movement. At $z = 100$ mm bubbles move towards the obstructed pipe section,
566 which indicates that no recirculating flow affects the lateral movement anymore.
567 Further downstream at $z = 400$ mm, the lateral bubble velocity field shows only
568 statistical movement and rather low velocities of bubbles.

569

570 **4 Conclusion**

571 We experimentally studied the two-phase flow around two different flow
572 constrictions using UFXCT imaging technique. A baffle-shaped and a ring-shaped
573 type of flow constriction were used to induce generic three-dimensional flow fields
574 in a vertical DN50 pipe. We studied the flow at various gas and liquid superficial
575 velocities in vertical co-current upward flow under nearly adiabatic conditions.
576 From UFXCT technique phase distributions and bubble sizes were obtained with
577 high temporal and spatial resolution. Therefore, an enhanced data processing
578 procedure was developed to increase the reliability of the image data. The data is
579 available as a benchmark data set at the Rossendorf Data Repository (RODARE)
580 [30,31].

581 In this paper, we exemplarily analyzed flow conditions for the cases of varying
582 liquid superficial velocities and fixed gas superficial velocity of $j_g = 0.0368 \text{ m}\cdot\text{s}^{-1}$. In
583 case of baffle-shaped flow constriction, sectional views of the time-averaged gas
584 holdup revealed the change of gas accumulation from upstream to downstream
585 position with increasing liquid superficial velocity. In case of ring-shaped flow
586 constriction less gas accumulation was found. However, the bubble size
587 distribution as well as the mean bubble diameter showed similar trends along the

588 test section pipe for both flow constrictions. Eventually, lateral bubble velocity
 589 fields for the baffle-shaped flow constriction revealed clear lateral movement of
 590 the bubbles downstream of the constriction towards the obstructed side of the
 591 test section pipe in case of lower liquid superficial velocity. In contrast, nearly no
 592 lateral movement was found in this area, but directly upstream of the constriction
 593 in case of higher liquid superficial velocity.

594

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 598 German Bundestag.

599 **6 Nomenclature**

<i>Latin letters</i>	
a	offset for calculation of $\bar{\mu}_{i,j}^{(\text{gas})}$
B	single identified Bubble
D and d	diameter (mm)
f	image frequency per scanning plane
F	cross-correlation function
H	frequency of occurrence (%/mm)
j	superficial velocity ($\text{m}\cdot\text{s}^{-1}$)
L and l	length (mm)
Δm	plane distance map (mm)
N	total number
R	radius (mm)

Δt	time shift (ms)
u	velocity ($\text{m}\cdot\text{s}^{-1}$)
w	pixel weights
x, y	space coordinates (mm)
z	relative measurement height (mm)
<i>Greek letters</i>	
ε	gas holdup (%)
ε_m	mean value of Gaussian distribution function fitted to gas holdup histogram
μ	attenuation coefficient in (mm^{-1})
μ_μ	mean value of Gaussian distribution
<i>Super- and subscripts</i>	
ax	axial
b	bubble identifier
B	bubble
bin	binarized data set
gas and g	gaseous phase
Id	identifier data set
i, j	space coordinates (pixel)
k	time coordinate (ms)
lat	lateral
liq and l	liquid phase
low and up	scanning plane identifier
ref	reference pixel

tp	two-phase flow data set
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600

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