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1 Experimental investigations on a common centrifugal 2 pump operating under gas entrainment conditions

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8 **Abstract**

9 This paper presents an experimental study on the effects of additional gas entrainment in
10 centrifugal pumps designed for conveying liquid phases only. The pump performance has
11 been evaluated for several gas entrainment conditions, and for various operational settings
12 of the pump, such as its alignment and the rotational speed of the impeller. As a main
13 performance indicator the impact of entrained gas on the hydraulic power of the pump has
14 been analyzed using experimental data. Additionally, high-resolution gamma-ray computed
15 tomography (HireCT) operated in time-averaged rotation-synchronized scanning mode has
16 been applied to quantify local phase fraction distributions inside the rapidly rotating pump
17 impeller. Based on these quantitative tomographic measurements, gas holdup profiles along
18 selected streamlines have been calculated and gas accumulation areas inside the impeller
19 chambers have been visualized. Thus, various internally accumulated gas holdup patterns
20 have been identified and, eventually, associated with characteristic pump performance
21 behaviors. Moreover, the tomographic measuring method allowed an enhanced gas holdup
22 analysis in specified pump compartments. As a result, the related specific gas and liquid
23 phase holdup profiles have been evaluated.

24 **Keywords:** centrifugal pump, gas entrainment, two-phase flow, gas holdup, gamma-ray
25 computed tomography

26 **1. Introduction**

27 The reliable operation of pumps in power stations is essential for highly available, efficient
28 and safe generation of electricity. For example, in nuclear power stations with light water
29 reactors, emergency core cooling systems are operated with centrifugal pumps. During a

30 loss-of-coolant accident (LOCA) they continuously convey the coolant to steadily discharge
31 all decay heat produced inside the core. Therefore, coolant is taken from reservoirs, which
32 are, for example, the condensation chambers or the reactor sump. Since the coolant in these
33 reservoirs has free surfaces, gas entrainment due to hollow vortex formation may occur. The
34 vortex formation is initiated by small surface vortices, which are always present in such
35 reservoirs, and can lead to large developed gas entraining hollow vortices (Hecker, 1981).
36 This process depends on various conditions, such as the suction rate of the coolant, the
37 critical submergence of the intake and its geometry, as well as the fluid properties of the
38 coolant (Caruso et al., 2014; Kimura et al., 2008). Gas entrainment into the coolant results in
39 a gas/liquid two-phase flow, which passes the subsequently connected system components
40 of the cooling circuit, like pumps and valves. Preferably, gas entrainment should be avoided,
41 since these system components are usually designed for single-phase liquid flow and the
42 entrained gas may lead to undesired operational states, attended by vibrations and
43 increased mechanical load, which can even damage these components.

44 In the past, several experimental and numerical studies have been performed, to investigate
45 the operation behavior of centrifugal pumps under various operation conditions. Operation
46 of centrifugal pumps under single-phase flow conditions has been investigated, for example,
47 regarding effects like flow induced pressure pulsations and resulting vibrations and noise
48 (Suhane, 2012) or during start up (Zhang et al., 2013). Furthermore, effects of unsteady flow
49 patterns, resulting from pressure fluctuations, on the pump operation have been analyzed,
50 using numerical models (Gonzales and Santolaria, 2006). Also the influence of the impeller
51 geometries on the hydrodynamics of centrifugal pumps have been numerically investigated
52 and improved designs have been verified (Grapsas et al., 2007; Zhou et al., 2013).

53 Moreover, observations on centrifugal pumps operating under two-phase flow conditions
54 have been reported. Amongst others, scale model pumps were analyzed in the event of a
55 LOCA by conducting blow down test (Narabayashi et al., 1985) or a full-size nuclear reactor
56 pump was experimentally investigated under high pressure steam/water two-phase flow
57 conditions (Chan et al., 1999). Furthermore, in comparison to experimental results, the gas
58 fraction, pressure and velocity in the impeller of a centrifugal pump were numerically
59 calculated, applying Reynolds-averaged Navier-Stokes equations (Pak and Lee, 1998), or
60 consequences of two-phase flow due to cavitation were identified (Duplaa et al., 2013; Tan
61 et al., 2013; Coutier-Delgosha et al., 2003). Another numerical study was focused on the

62 influence of bubble diameter and void fraction of entrained gas on the pump operation
63 (Caridad et al., 2008). Recently, the gas accumulation inside a closed impeller of an industrial
64 centrifugal pump under various gas entrainment conditions has been quantified, and
65 corresponding gas holdup areas have been visualized, using high-resolution gamma-ray
66 computed tomography (Schäfer et al., 2015; Neumann et al., 2016).

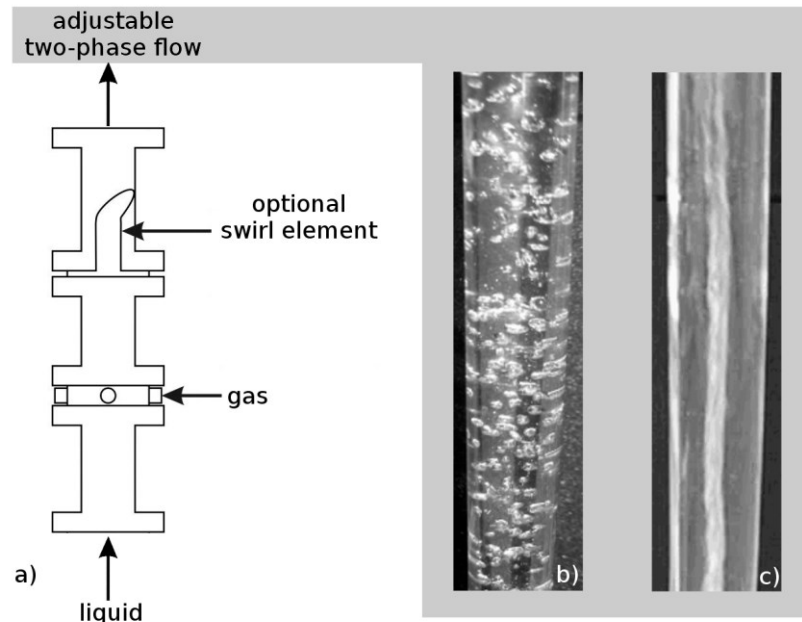
67 This study contributes to a better understanding of the impacts of gas entrainment on the
68 performance of centrifugal pumps and provides additional knowledge to operate centrifugal
69 pumps under such conditions or even to improve the pump design correspondingly. Besides,
70 additional datasets are provided for a better modelling of two-phase flows in centrifugal
71 pumps, which may improve future CFD calculations.

72 **2. Materials and methods**

73 In this experimental study a common industrial centrifugal pump (Etachrom BC 032-160/074
74 C11, KSB) has been investigated, equipped with a closed radial multi vane impeller. The
75 centrifugal pump can be installed either horizontally or vertically, regarding to the impeller
76 orientation, and it is connected to a flow loop, where a defined gas-liquid two-phase flow is
77 circulated by the investigated pump itself. For the experiments, tap water is used as liquid
78 phase and de-oiled pressurized air as gas phase. The liquid is stored in a 600 l reservoir. The
79 liquid flow rate is measured by a magnetic inductive liquid flow meter (MAG 1100, Siemens).
80 The liquid flow meter and a liquid temperature sensor (PT100) are installed upstream of the
81 pump, between the liquid reservoir and an in-house developed gas injection module. Here,
82 gas is injected via four hole-type nozzles, which are uniformly arranged around the
83 circumference of the pipe. The gas injection module is installed at the suction side of the
84 pump and provides an adjustable gas-liquid two-phase flow. The injected gas volume
85 fraction ε_{in} ($0 \leq \varepsilon_{in} < 1$) can be adjusted and the required gas flow rate Q_G is controlled by
86 an air mass flow controller (FMA2600, Omega Newport), which is triggered by a
87 programmable logic controller (SPS-ILC350ETH, Phoenix Contact) considering the current
88 liquid flow rate Q_L according to

$$89 \quad Q_G = \frac{\varepsilon_{in}}{1 - \varepsilon_{in}} \cdot Q_L. \quad (1)$$

90 Optionally, a sophisticated swirl element can be installed inside the gas injection module
91 behind the gas inlet nozzles to adjust the flow regime of the two-phase flow (Figure 1a). Thus, for the experiments, both typical flow regimes, occurring at gas entrainment due
92 to hollow vortex formation, can be provided at the suction side of the pump. These are
93 either a gas-liquid flow with disperse gas phase (“bubbly two-phase flow”) (Figure 1b) or a swirling gas-liquid flow with central formed gas core (“swirling two-phase flow”)
94 (Figure 1c).
95
96



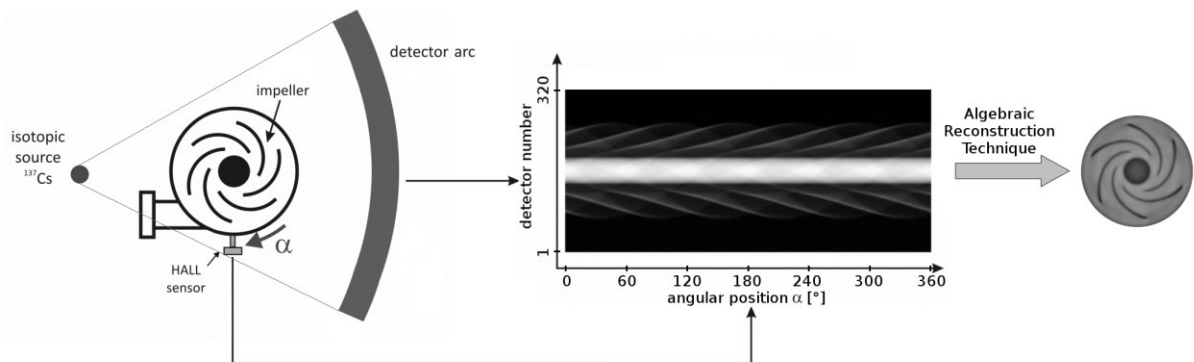
97

98 Figure 1: a) Sketch of the multi-mode gas injection module and adjustable flow regimes: b)
99 gas-liquid flow with disperse gas phase (“bubbly two-phase flow”) and c) swirling
100 gas-liquid flow with central formed gas core (“swirling two-phase flow”).

101 Furthermore, a heat exchanger (C200 301-1, Funke) in combination with a controlled
102 thermostat (Unistat Tango) is installed in the flow loop at the pressure side of the centrifugal
103 pump to provide a constant liquid temperature of $T = 30^{\circ}\text{C}$ for the experiments. The two-
104 phase flow is conveyed from the gas injection module through the centrifugal pump and the
105 heat exchanger back to the liquid reservoir which acts also as a two-staged separator. Here,
106 the injected gas phase is separated from the liquid phase. Furthermore, the flow loop is
107 instrumented with two pressure sensors to measure the relative pressure at the suction side
108 (PR23, Omega Newport) and the differential pressure across the pump (PD23, Omega
109 Newport).

110 Additionally, high-resolution gamma-ray computed tomography (HireCT) (Hampel et al.
 111 2007; Bieberle et al., 2012, 2013; Schubert et al., 2011) has been applied to discover the
 112 phase distribution inside the operating pump impeller by contactless measurement. The
 113 HireCT-system is able to scan objects, which have a maximal diameter of 700 mm. It consists
 114 of a temperature stabilized detector arc including 320 scintillation detector elements with a
 115 sensitive area of 2 mm x 4 mm and is operated with a collimated isotopic source (^{137}Cs ,
 116 energy: 662 keV, activity: 180 GBq). The investigated centrifugal pump was placed between
 117 the source and the detector arc, which are both fixed on a movable desk.

118 To resolve the phase fraction distribution inside the fast rotating impeller of the operating
 119 pump sharply, tomographic scans are synchronized with the rotational speed of the impeller
 120 (Figure 2). Therefore, the rotational speed is measured, using a Hall-effect sensor
 121 (GS105502, ZF Electronics). The Hall-effect sensor is placed close to the driving shaft and is
 122 connected directly to the HireCT-scanner. This advanced CT measuring method, which is
 123 known as time-averaged rotation-synchronized computed tomography, was introduced by
 124 (Prasser et al., 2003) for investigations on an axial pump and further developed by (Hampel
 125 et al., 2005, 2008; Bieberle et al., 2007).



126
 127 Figure 2: Sketch of HireCT measurement setup (left), data set of measured projections
 128 referred to as “sinogram” (middle) and reconstructed attenuation image of the
 129 scanned rotating impeller (right).

130 Applying algebraic reconstruction techniques (ART) (Gordon et al., 1970), non-superimposed
 131 cross-sectional images of the attenuation coefficients μ_{ij} , where i and j represent the
 132 indices of the image pixels, can be reconstructed from a complete tomographic scan (Figure
 133 2). These images represent the spatial material distribution inside the scanned
 134 object, which also includes time-averaged information about the phase fraction distribution

135 of the conveyed gas-liquid mixture inside the pump. This phase fraction distribution can be
 136 visualized and also quantified, by referring the measured distribution of the relative linear
 137 attenuation coefficients of the investigated pump under two-phase flow conditions μ_{ij}^{TP} to
 138 tomographic scans of defined material distributions (reference states). Thus, the local
 139 quantitative gas phase fraction ε_{ij} is calculated according to

$$140 \quad \varepsilon_{ij} = \frac{\mu_{ij}^L - \mu_{ij}^{TP}}{\mu_{ij}^L - \mu_{ij}^G}, \quad (2)$$

141 where μ_{ij}^L and μ_{ij}^G are the spatial distributions of the relative linear attenuation coefficients
 142 of the reference states. Here, μ_{ij}^L equates to 0% gas (pump completely filled with water) and
 143 μ_{ij}^G equates to 100% gas (drained pump). The actual spatial resolution of the phase fraction
 144 distributions based on the tomographic scans is approximately 2 mm and the measuring
 145 uncertainty of the HireCT system regarding the determined quantitative phase fraction
 146 values is $\leq \pm 0.01$, which has been proven in a prior study (Bieberle et al., 2015).

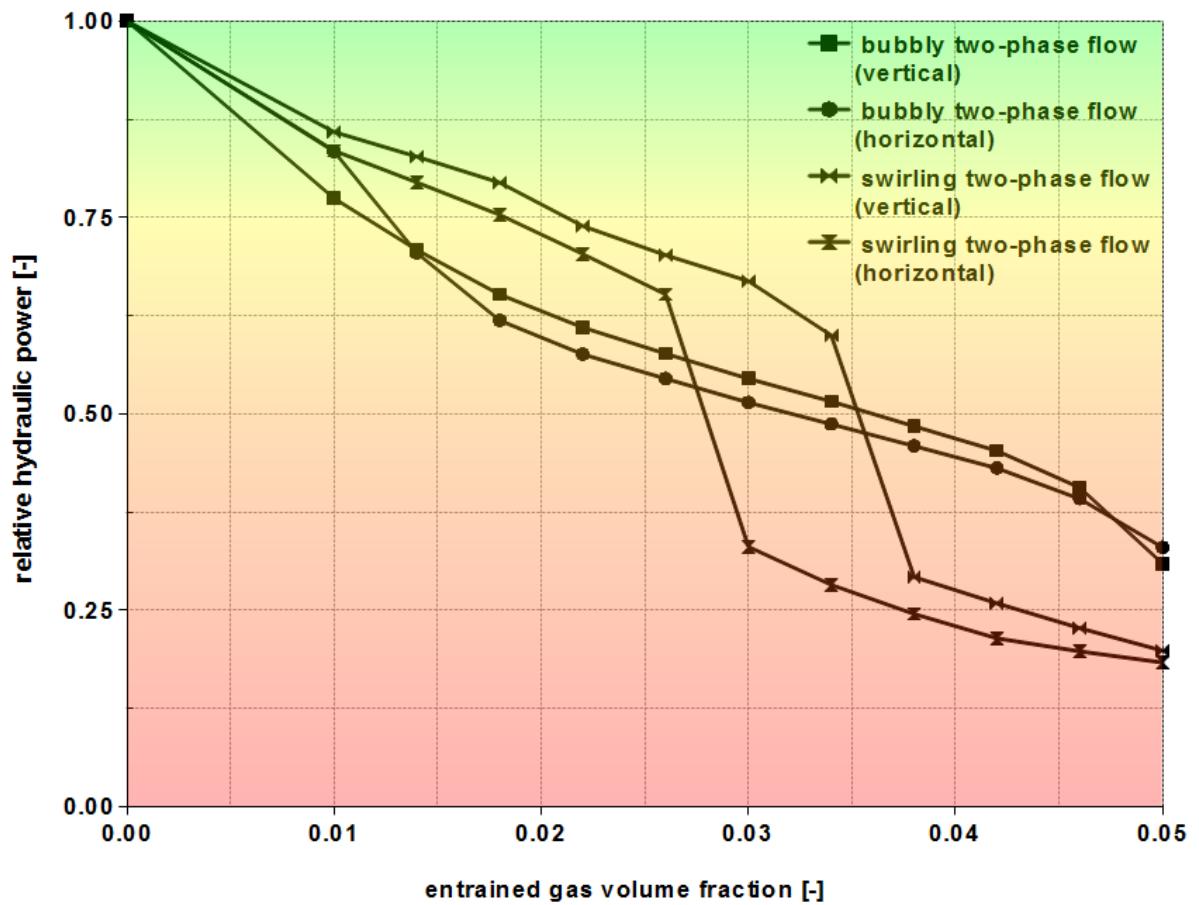
147 **3. Results**

148 **3.1 Influence of gas entrainment on the pump performance**

149 The performance of the centrifugal pump under gas entrainment conditions is one of the
 150 main issues, since the investigated pump was designed for conveying liquids only. Thus, the
 151 pump performance at nominal speed (1480 rpm) is experimentally investigated for both
 152 pump alignments (horizontal and vertical impeller) and for several gas entrainment
 153 conditions. Therefore, the injected gas volume fraction ε_{in} as well as the suction side flow
 154 regime (“bubbly two-phase flow” / “swirling two-phase flow”) is varied. Based on the
 155 associated conveyed liquid flow rates Q_L and the corresponding differential pressures across
 156 the pump Δp , the relative hydraulic power is calculated according to

$$157 \quad P_{hyd,rel}(\varepsilon_{in}) = \frac{P_{hyd}(\varepsilon_{in})}{P_{hyd}(\varepsilon_{in} = 0)} = \frac{Q_L(\varepsilon_{in}) \cdot \Delta p(\varepsilon_{in})}{Q_L(\varepsilon_{in} = 0) \cdot \Delta p(\varepsilon_{in} = 0)}. \quad (3)$$

158 | The resulting performance curves of the pump are shown in [Figure 3](#), where the
 159 relative hydraulic power is plotted against the entrained gas volume fraction, depending on
 160 the flow regime at the suction side and the alignment of the impeller.



161

162 Figure 3: Performance curves for both installation positions (horizontal and vertical impeller
 163 alignment) and various gas entrainment conditions and gas volume fractions.

164 Generally, the relative hydraulic power of the pump decreases with increasing gas
 165 entrainment. In case of bubbly two-phase flow the relative hydraulic power decreases
 166 continuously, down to nearly 30% of the undisturbed hydraulic power. Here, an almost
 167 identical curve was found for both installation positions. This indicates that the impeller
 168 alignment has no significant impact on the hydraulic power in case of gas entrainment by
 169 bubbly two-phase flow. But in contrast to the continuous decrease of relative hydraulic
 170 power at bubbly two-phase flow inlet condition, a remarkable performance discontinuity
 171 was observed for both impeller alignments at swirling two-phase flow inlet condition, where
 172 the relative hydraulic power decreases steeply down to less than 30%. After that, a further
 173 more gently decrease of the relative hydraulic power down to nearly 20% can be observed.
 174 Thus, gas entrainment by swirling two-phase flow regime leads to a higher performance
 175 drop compared to bubbly two-phase flow regime at same gas volume fraction injection. The
 176 observed hydraulic power discontinuity, which is represented by an abrupt performance

177 drop, occurs at entrained gas volume fractions between $0.026 < \varepsilon_{in} < 0.030$ for the
178 horizontal case, but for the vertical case it happens at slightly higher entrained gas volume
179 fractions between $0.034 < \varepsilon_{in} < 0.038$. Here, the alignment of the impeller wheel has
180 probably a considerable impact.

181 **3.2 Gas holdup accumulation inside the impeller**

182 To study the observed discontinuous performance drop, a set of tomographic scans of the
183 pump with horizontally aligned impeller, operating at 1480rpm, were conducted. The
184 obtained and reconstructed images of the investigated two-phase flow inside the impeller
185 | ([Figure 4](#)~~Figure-4~~) disclose a remarkable evolution of the phase fraction distribution
186 depending on the entrained gas volume fraction. This is represented in detail in holdup
187 curves, calculated from the tomographic measurement data for three different radially
188 | arranged impeller areas. These areas are indicated in [Figure 4](#)~~Figure-4~~ and are artificially
189 defined in the measurement plane in radial direction as the inlet area (impeller suction eye,
190 where the fluid enters the impeller), the chamber area (impeller vanes, where the fluid is
191 accelerated) and the outlet area (clearance between the impeller shrouds and the casing,
192 where the fluid is decelerated). Furthermore, the mean value of all curves was calculated
193 | and plotted ([Figure 4](#)~~Figure-4~~).

194 | Obviously, two states are represented in all holdup curves in the diagram in [Figure 4](#)~~Figure-4~~,
195 depending on the entrained gas volume fraction and indicating different flow characteristics
196 inside the pump. They can be assigned to the conditions before and after the performance
197 transition which occurs at entrained gas volume fractions between 0.026 and 0.030 and
198 | which was already found in the hydraulic power curve ([Figure 3](#)~~Figure-3~~) for the gas
199 entrainment by swirling two-phase flow.

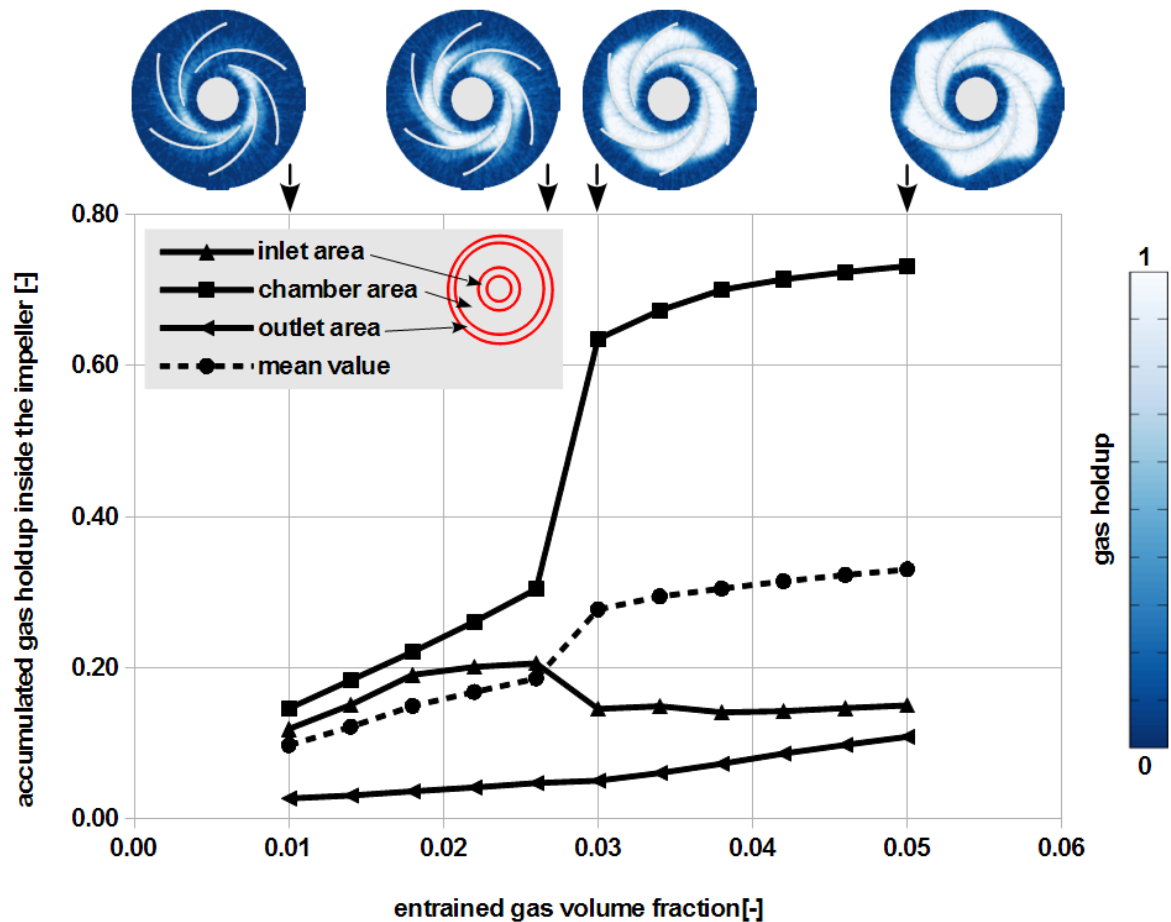
200 | The gas holdup curve of the inlet area ([Figure 4](#)~~Figure-4~~) is characterized by a strong linear
201 increase, which can be found at lower entrained gas volume fractions (< 0.018) and indicates
202 a high degree of phase separation and gas accumulation in this area. This is preceded by a
203 slightly decreasing slope of the holdup curve (at entrained gas volume fractions between
204 0.018 and 0.026), which indicates a decreasing phase separation of the two-phase flow
205 under this conditions, where more of the entrained gas is conveyed with the liquid. Thus,
206 only a slightly increase of accumulated gas can be found in this impeller area. Here, typical
207 gas holdup values of about 0.2 can be found. Following this, an abrupt holdup drop occurs in

208 this impeller area at entrained gas volume fractions between 0.026 and 0.030. Now, less
209 phase separation takes place and large amount of prior accumulated gas is displaced by the
210 liquid phase again. This leads to a more homogeneous two-phase flow, which dominates the
211 area again. Consequently, a noticeable drop of accumulated gas holdup down to 0.14 is
212 observable. This reduced holdup value then remains stable, although the entrained gas
213 volume fraction is further increasing.

214 The gas holdup in the chamber area is also continuously increasing at lower entrained gas
215 volume fractions (< 0.018). Here, nearly the same slew rate as in the inlet area is observable.
216 This indicates again a high phase separation rate, which leads to growing accumulated gas
217 pockets and results in decreasing energy transfer from the impeller blades to the liquid
218 phase. But, in contrast to the inlet area no stagnation or drop of phase separation and lower
219 gas accumulation (saturation) can be found for entrained gas volume fractions between
220 0.018 and 0.030. During the flow transition (at entrained gas volume fractions between
221 0.026 and 0.030), also in contrast to the inlet area, the phase separation and thus the gas
222 holdup is increasing very strong. Subsequently, after the transition, only a slightly increasing
223 holdup was detected, which indicates stagnation (saturation) of the gas accumulation
224 capacity in the chamber area under these conditions. While the entrained gas at lower
225 entrained gas volume fractions (≤ 0.026) is exclusively accumulated near to the inlet of the
226 impeller chamber area, there is an appreciable different distribution at higher volume
227 fractions (≥ 0.03). Here, nearly the entire impeller chamber area is filled with gas, which
228 strongly constrains the energy transfer from the impeller blades to the liquid phase, because
229 of losses due to slip between the phases and the compressibility of the gas.

230 Also, the relative total amount of accumulated gas in the impeller chambers strongly differs
231 for both conditions. While at lower volume fractions about the twelve to fifteen fold of the
232 entrained gas volume fraction is accumulated inside the impeller chamber area, it is much
233 more after the transition. The rapid change of the phase distribution inside the impeller
234 chamber area indicates that the flow regime and thus, the hydrodynamic conditions inside
235 the impeller wheel must have changed rapidly, which leads to more phase separation along
236 the flow inside the chambers. This means, the type of suction side two-phase flow regime
237 has a critical impact on the hydrodynamic conditions inside the impeller wheel and thus, on
238 the performance and reliability of the centrifugal pump.

239 In the outlet area, in general, only small amounts of accumulated gas can be found and the
 240 holdup values are only slightly increasing over the whole range of entrained gas volume
 241 fraction, which was chosen for the investigations. However, here also a transition is
 242 observable, which is indicated by a very small change of slope after the critical entrained gas
 243 volume fraction of 0.03.



244

245 Figure 4: Gas holdup accumulation inside the impeller of an industrial centrifugal pump,
 246 operating at 1480 rpm, depending on the entrained gas volume fraction, for
 247 horizontal impeller orientation and gas entrainment by swirling two-phase flow
 248 with central formed gas core.

249 **3.3 Impact of rotational speed**

250 Furthermore, the effect of rotational speed of the centrifugal pump impeller on the
 251 accumulated gas holdup inside the impeller, depending on the impeller orientation and the
 252 entrained gas volume fraction, has been investigated for two different gas entrainment
 253 conditions. These are gas entrainment by bubbly two-phase flow (Figure 5a) and gas
 254 entrainment by swirling two-phase flow (Figure 5b). Therefore, the rotational speed was

255 varied and the pump was operated, besides nominal speed (1480 rpm), at lower (1300 rpm)
256 and higher (1600 rpm) rotational speed.

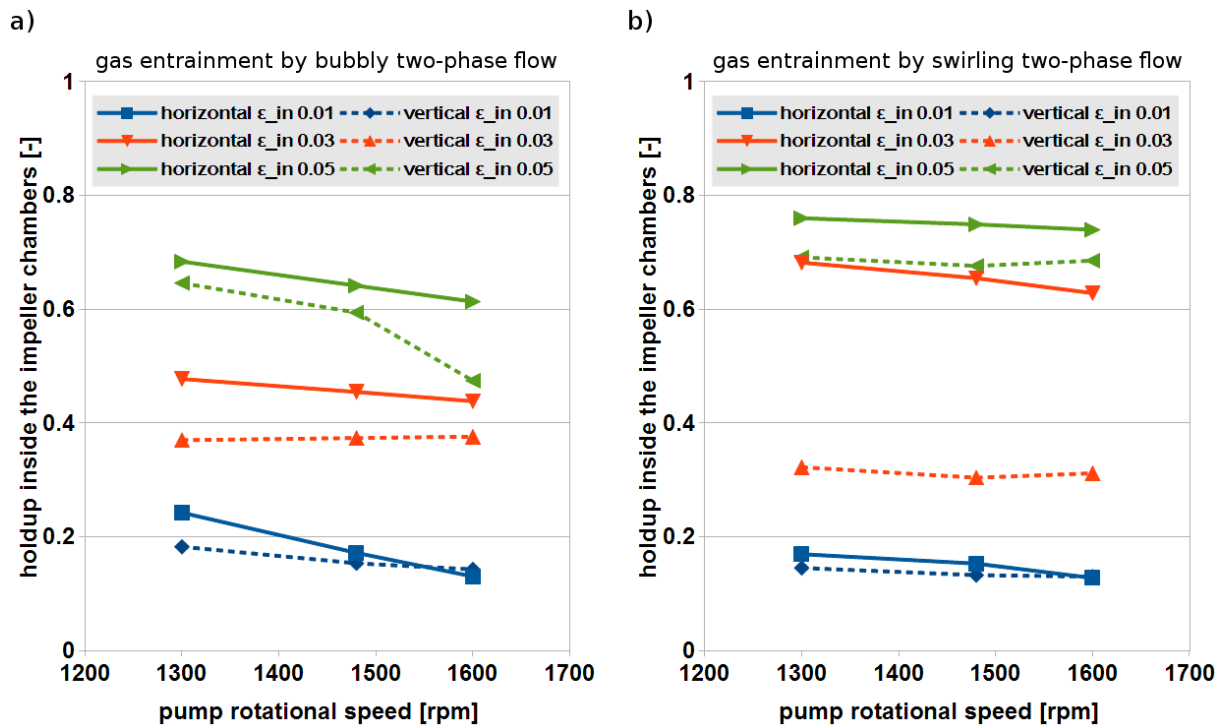
257 It was found that the rotational speed of the impeller has only a very small influence on the
258 amount of accumulated gas inside the impeller chambers if gas is entrained by swirling two-
259 phase flow (Figure 5b). In the case of the vertical alignment of the impeller the gas holdup
260 stays nearly constant over a wide range of rotational speed, while the gas holdup is slightly
261 decreasing if the impeller is horizontally arranged.

262 If gas entrainment takes place under bubbly two-phase flow conditions (Figure 5a) the
263 rotational speed has a stronger impact on the amount of accumulated gas. Here, with
264 increasing rotational speed the gas holdup is slightly decreasing. This can be explained by a
265 better energy transfer from the impeller blades to the liquid phase of the two-phase flow.
266 While the radial acceleration is increasing at higher rotational speeds, the phase separation
267 of the homogeneous bubbly two-phase flow inside the impeller chambers is constrained.
268 Thus, the present disperse gaseous phase is better carried out from the impeller chamber,
269 together with the liquid. Furthermore, the holdup is decreasing nearly linear with increasing
270 rotational speed, if the impeller wheel is horizontally arranged. This indicates the continuous
271 impact of the rotational speed and therewith the radial acceleration on the two-phase flow,
272 which is, at least for the investigated range of entrained gas in the experiments
273 ($0.01 \leq \varepsilon_{in} \leq 0.05$), independent from the amount of entrained gas. In contrast, deviant,
274 nonlinear behavior was found for the vertical arranged impeller at higher rotational speed
275 (1600 rpm) and for higher gas entrainment rates (gas volume fraction 0.05). For this case a
276 strong decrease of the accumulated gas holdup was observed. This indicates again the
277 positive impact of increasing rotational speed on conveying of bubbly two-phase flow. Thus,
278 independent from the impeller alignment, higher rotational speed results in higher radial
279 acceleration, which is advantageous for steadily conveying of bubbly two-phase flow.

280 In general it is identifiable, that the amount of accumulated gas inside the impeller chamber
281 depends on the impeller installation orientation. If the impeller is horizontally arranged the
282 gas holdup is always higher (in certain cases even significantly higher) than in the cases
283 where the impeller is vertically arranged. This behavior was found for nearly all investigated
284 operational conditions, except for very small gas entrainment (gas volume fraction 0.01) in
285 combination with very high rotational speeds (1600 rpm), where the accumulated gas

286 holdup remains nearly on the same level in both installation orientations. This indicates a
 287 stable, poorly separated two-phase flow inside the impeller chambers, which allows high
 288 conveyability of the two-phase flow.

289 Furthermore, a strong deviation in the amount of accumulated gas was found, depending on
 290 the impeller orientation, for gas entrainment by swirling two-phase flow with formed gas
 291 core (Figure 5b) and a gas entrainment volume fraction of 0.03. However, this is caused by
 292 the discontinuous flow transition, which was typically found only for gas entrainment by
 293 swirling two-phase flow with formed gas core, as already discussed before. Based on the
 294 results of the experiments, which are represented in the diagram in [Figure 4](#), it is
 295 known that the gas holdup inside the impeller is smaller before the transition takes place
 296 and it is much higher after this transition. Since the critical entrained gas volume fraction for
 297 this transition is depending on the impeller orientation ([Figure 3](#)), it is obvious, that
 298 the observed large holdup differences between the horizontal and the vertical case in the
 299 diagram in Figure 5b, for the entrained gas volume fraction of 0.03, are caused by this shift
 300 of transition.

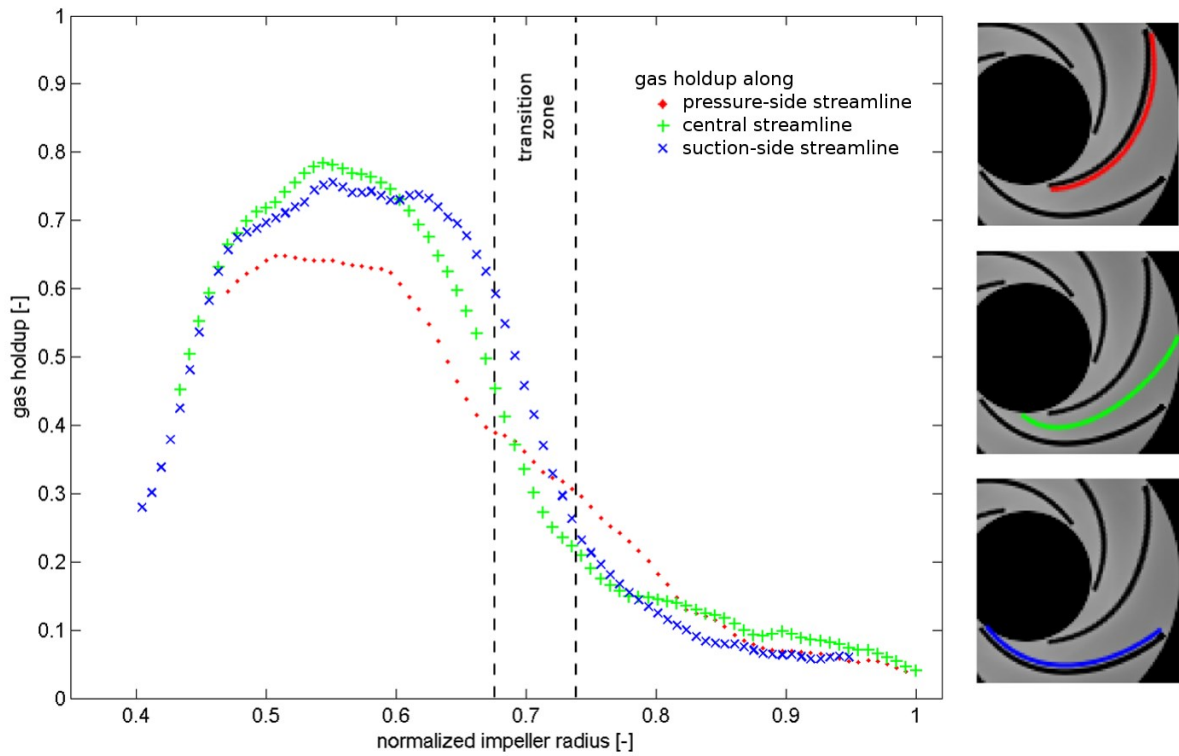


301
 302 Figure 5: Effect of rotational speed of the centrifugal pump on the gas holdup, depending
 303 on the impeller orientation and the entrained gas volume fraction, for gas
 304 entrainment by a) bubbly two-phase flow and b) swirling two-phase flow.

305 **3.4 Impact of a balancing hole**

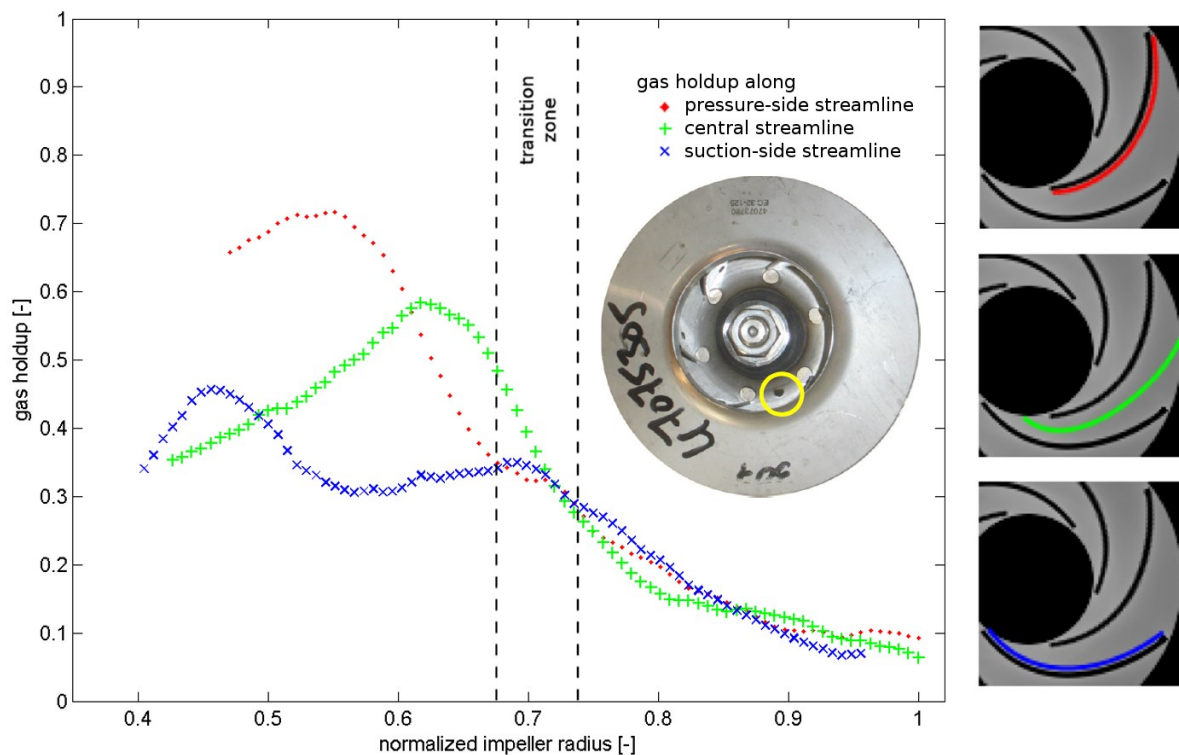
306 The impeller is featured with a balancing hole, which is drilled into the hub plate. It is
307 beneficial during start-up of the pump to relieve the bearing from axial thrust. Since a
308 previous study at nominal rotational speed has already shown, that the distribution of the
309 accumulated gas holdup inside the impeller chambers can be influenced by such a balancing
310 hole (Schäfer et al., 2015), this effect was investigated in more detail. Therefore, the gas
311 holdup profiles in the impeller chambers are analyzed along selected streamlines. These
312 selected streamlines are illustrated as colored lines on the right hand side in [Figure 6](#)
313 and [Figure 7](#). The associated discrete quantitative gas phase fraction values, based
314 on the reconstructed tomographic images, were weighted according to their affiliation to
315 the streamline and assigned to the gas holdup profiles along these selected streamlines. The
316 obtained gas holdup profiles are represented for gas entrainment by swirling two-phase flow
317 for $\varepsilon_{in} = 0.03$ and for an impeller revolution of 1900 rpm in the diagrams in [Figure 6](#)
318 and [Figure 7](#). While [Figure 6](#) represents the profiles of a chamber without a
319 balancing hole, [Figure 7](#) shows the profiles of a chamber equipped with such a
320 balancing hole. The profiles of the impeller chamber without a balancing hole ([Figure 6](#)
321 [6](#)) disclose a slight higher gas holdup in the inner area of the impeller (normalized radii
322 between 0.4 and 0.7) along the central and suction side streamlines than along the pressure-
323 side streamline. But, the gas holdup profiles of the impeller chamber, equipped with a
324 balancing hole ([Figure 7](#)), show a completely different behavior. Here, the gas
325 holdup in the inner impeller area along the central and suction side streamlines is much
326 smaller than along the pressure-side streamline. This indicates that the back flow from the
327 pressure side of the hub plate through the balancing hole into the inlet of the corresponding
328 impeller chamber displaces the common path of the incoming flow, which prevents the
329 phase separation and accumulation of a steady gas pocket and, thus, leads to a smaller gas
330 holdup along the central and suction-side area of this chamber. Only the gas holdup along
331 the pressure-side streamline is nearly similar compared to the chamber without a balancing
332 hole. The observed results illustrate the positive impact of the balancing hole, which reduces
333 the phase separation and the accumulation of gas inside the inner area of the impeller.
334 Furthermore, along all selected streamlines and in both impeller chambers a concordant gas
335 holdup value can be discovered at a normalized radius of about 0.7 (transition zone). This
336 indicates an almost homogeneous gas holdup distribution in tangential direction, between

337 the blades, at this radial position. Here, also a strong reduction of gas accumulation in radial
 338 direction, from the inner impeller area to the outer one, takes place. Consequently, this
 339 nearly homogeneous local gas holdup distribution in this area indicates that a part of the
 340 accumulated gas in the impeller chamber relocates, cross to the liquid flow direction, from
 341 the suction-side to the pressure-side, before it is discharged from the impeller chamber. The
 342 resulting gas-liquid phase mixing leads to a homogenization of the two-phase flow, which is
 343 beneficial for the energy transfer to the liquid and the conveying of the present two phase
 344 flow.



345

346 Figure 6: Observed gas holdup profiles along selected streamlines inside an impeller
 347 chamber without balancing hole.



348

349 Figure 7: Effect of a balancing hole on the gas holdup inside the corresponding impeller
 350 chamber.

351 **4. Conclusion**

352 In this study the effects of gas entrainment in centrifugal pumps, designed for conveying
 353 liquids only, have been experimentally investigated. Depending on different gas entrainment
 354 conditions, the impact on the hydraulic power of the pump has been analyzed and the
 355 influence of the pump installation position has been investigated. It has been discovered,
 356 that the gas entraining two-phase flow regime has a large impact on the pump performance.
 357 Gas entrainment by swirling two-phase flow regime has been found as more unfavorable
 358 compared to gas entrainment by bubbly two-phase flow, since it leads to a higher and
 359 discontinuous performance drop. But, regarding to the alignment of the pump no significant
 360 impact on the pump performance has been observed. However, for gas entrainment by
 361 swirling two-phase flow regime, a vertical impeller alignment leads to a slightly delayed
 362 discontinuous performance drop. Additionally, high-resolution gamma-ray computed
 363 tomography (HireCT), operated in time-averaged rotation-synchronized scanning mode, has
 364 been used to observe and quantify local gas-liquid phase fraction distributions inside the
 365 operating pump impeller. Based on these quantitative tomographic measurements, gas
 366 holdup profiles in different radially arranged impeller areas and along selected streamlines

367 have been calculated and analyzed. Thus, structures of gas accumulation inside the impeller
368 chambers have been detected and the impact of a balancing hole on the gas phase
369 accumulation inside the corresponding impeller chamber has been disclosed.

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