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HIGHLIGHTS

- Food aeration at pilot scale was investigated using two technologies and three surfactants.
- Whey proteins (WPC) are a better foaming agent than sodium caseinate (SCN) and tween 20 (TW20).
- Experimental data were confronted to the visualization of single bubble break-up under shear flow.
- WPC and SCN promoted bubble break-up by *tip streaming*; TW20 only deformed bubbles.
- Single bubble break-up needs higher shear with WPC than SCN, but kinetic limitations appear with SCN during aeration.

1 **Food aeration: effect of the surface-active agent type**
2 **on bubble deformation and break-up in a viscous Newtonian fluid:**
3 **from single bubble to process-scale**

4
5 B. SANOGO^{1*}, K. SOUIDI^{1,2}, A. MARCATI¹, C. VIAL¹

6 ¹Université Clermont Auvergne, CNRS, Clermont Auvergne INP, Institut Pascal, F-63000,
7 Clermont-Ferrand, France

8 ²Université La Réunion, CIRAD, Université Montpellier, Institut Agro Montpellier, IRD,
9 Université Avignon, Qualisud, F-97490 Sainte Clotilde, France

10
11 *Corresponding author: boubakar.sanogo@uca.fr

12
13
14 **Abstract**

15
16 Two continuous whipping devices, a rotor-stator (RS) and a narrow angular gap unit (NAGU), were
17 used to produce aerated food with a 25% (v/v) gas fraction target. The liquid phase was a Newtonian
18 model-solution containing 2% (w/w) of either whey proteins (WPC), sodium caseinate (SCN), or
19 tween 20 (TW20). Strong differences emerged regarding gas incorporation and bubble size as a
20 function of process parameters: namely, rotation speed and residence time. To improve understanding
21 of the results obtained at pilot-scale, a second investigation consisting in the observation of the
22 deformation and break-up of single gas bubbles has been undertaken using successively a Couette
23 device and an impeller close to NAGU. For proteins, the observation of single bubble deformation
24 and break-up showed that bubble break-up occurred by *tip-streaming* above a well-defined critical
25 Capillary number Ca_c of 0.27 and 0.5 for SCN and WPC, respectively, whereas no break-up was
26 observed with TW20 even though Ca reached 10. The poor foaming ability obtained with TW20
27 could be explained by a poor break-up mechanism, promoting coalescence and gas plugs at high shear
28 instead of gas incorporation. Conversely, protein promote tip-streaming as the major break-up
29 mechanism at low shear rate, explaining why rotation speed is not a key process parameter.
30 Differences observed between SCN and WPC can be attributed to diffusion limitation for SCN when
31 a much larger surface area is generated during aeration.

32
33 **Keywords:** continuous aeration process, bubble break-up, tip-streaming, simple shear flow, protein,
34 surfactant

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48 **Nomenclature**

49

50 **Dimensionless numbers**

51

52 Ca: Capillary number

53 Ca_c : critical Capillary number

54 Re : Reynolds number

55

56 **Abbreviations**

57

58 BSA: bovine serum albumin

59 BSD: bubble size distribution

60 HMW: high molecular weight

61 LMW: low molecular weight

62 NAGU: narrow angular gap unit device

63 RS: rotor-stator device

64 SAA: surface-active agent

65 SCN: sodium caseinate

66 TW20: tween 20

67 WPC: whey protein concentrate

68

69 **Greek symbols**

70

71 $\dot{\gamma}$: shear rate (s^{-1})

72 ε : experimental gas volume fraction (%)

73 ε_{max} : theoretical gas volume fraction (%)

74 η_c : viscosity of the continuous phase (Pa.s)

75 λ : viscosity ratio (-)

76 ρ_l : liquid density ($kg.m^{-3}$)

77 ρ_f : foam density ($kg.m^{-3}$)

78 σ : equilibrium surface tension ($N.m^{-1}$)

79 τ : shear stress (Pa)

80

81 **Latin characters**

82

83 a : radius of the initial bubble (m)

84 B : half-length of the minor axis (m)

85 D : deformation parameter (-)

86 D_{in} : initial bubble diameter (m)

87 D_{mean} : average bubble diameter (m)

88 $e_{Couette}$: gap between cylinders (m)

89 G_i : gas flow rate ($m^3.s^{-1}$)

90 L : half-length of the major axis (m)

91 L_i : liquid flow rate ($m^3.s^{-1}$)

92 N : rotor speed (s^{-1})

93 R_i : radius of inner cylinder (m)

94 \bar{t} : residence time (s)

95 1. INTRODUCTION

96

97 Foam-based products are found and very common in the food industry with products such as cake
98 batter, ice-cream, whipped cream, etc. Foams are a dispersion of gas bubbles in a liquid or solid
99 matrix [Stevenson, 2012; Cantat et al., 2013]. During the foaming process, mechanical shearing
100 forces are typically employed to break the dispersed gas phase into small bubbles, leading to a
101 substantial increase in surface area. Adding surface-active agents (SAA) is an effective approach to
102 reduce surface tension [Ho et al., 2021] by decreasing the work required to generate foams. There has
103 been a huge number of published papers on food aeration, focused on the properties of SAA
104 [Bezelgues et al., 2008; Zhang et al., 2013], the rheology of the fluid phases as well as surface tension
105 [Séguineau de Préval et al., 2014; Mezdour et al., 2017], the geometry of the processing apparatus
106 [Müller-Fischer and Windhab, 2005; Narchi et al., 2011], and the specific processing parameters
107 [Jabarkhyl et al., 2020; Badve, 2021]. Most of these studies investigated food aeration with a “black-
108 box” approach at pilot-scale, i.e., analyzing the effect of process parameters on the overrun and
109 stability of the foams produced without focusing on how the gas phase is dispersed inside the foaming
110 device. There is still, however, much to understand regarding the primary break-up of bubbles during
111 aeration. Understanding this primary break-up process could play a significant role in improving foam
112 formation. A common starting point is the break-up of a single bubble.

113 The break-up of a single bubble or droplet has been a topic of long-term interest due to the
114 common appearance of this phenomenon in various fields of engineering (food processing, emulsion
115 formation, aerosols, etc.). A pioneering investigation of steady simple shear flows was performed by
116 Taylor [1932; 1934]. It was found that when inertia is negligible, i.e., very low Reynolds number
117 (Re), the deformation of the drop prior to its break-up is mainly governed by the viscosity ratio (λ) of
118 the phases and the Capillary number (Ca). Ca is the ratio between the viscous stress which acts to
119 deform the bubble and the stabilizing Laplace pressure. Ca is defined by Eq. (1) where η_c is the liquid
120 viscosity, $\dot{\gamma}$ the shear rate, d_i the bubble initial diameter, and σ the equilibrium surface tension.

$$121 \quad Ca = \frac{\eta_c \dot{\gamma} d_i}{2\sigma} \quad (1)$$

122

123 Taylor [1934] also introduced the deformation parameter D Eq. (2) frequently used for small
124 deformations ($Ca \ll 1$) where L is the half-length of the major axis and B the half-length of the minor
125 axis of the deformed (ellipsoidal) bubble.

$$126 \quad D = \frac{L - B}{L + B} \quad (2)$$

127

128 For $Ca \ll 1$ and $\lambda \ll 1$, the bubble is nearly spherical with $D \approx Ca$. This theory has been fully
129 validated by experiments [Torza et al., 1971] and numerical simulations [Rallison, 1981].

130 At large deformation ($Ca \gg 1$), D tends to a limiting value of 1 and becomes useless. Beyond, the
131 parameter L/a must be used to measure the deformation (a is the initial nondeformed bubble radius).
132 A power law was often proposed to correlate the L/a parameter to Ca :

$$133 \quad \frac{L}{a} = \alpha Ca^\beta \quad (3)$$

134 where α and β are constants. Using the slender body theory and assuming that bubbles are circular in
135 cross section, Hinch and Acrivos [1980] predicted for $Ca \gg 1$, $\lambda \ll 1$, and $Re \ll 1$ that:

136

137
$$\frac{L}{a} = 3.45 Ca^{0.5} \quad (4)$$

138
139 **Canedo et al. [1993]** studied experimentally the deformation of air bubbles suspended in polybutene
140 in a Couette device and found that bubble cross-sections were elliptical and suggested a slightly
141 different law of deformations versus Ca (range 3 to 50):

142
143
$$\frac{L}{a} = 3.1 Ca^{0.43} \quad (5)$$

144
145 **Rust and Manga [2002]** and **Müller-Fischer et al. [2008]** performed the most recent studies on bubble
146 behavior under stress. **Rust and Manga [2002]** were interested in the measurements of the shape and
147 orientation of air bubbles in a viscous Newtonian fluid deformed by simple shear. Their data indicated
148 that for extremely small Re and λ , the deformation parameter D was a good approximation for $Ca <$
149 0.5 . **Müller-Fischer et al. [2008]** used two different visualization devices to monitor bubble behavior
150 in simple shear until break-up occurs.

151 A bubble in a steady flow deforms until the interfacial stress which holds it together can no longer
152 counterbalance the viscous stresses. Ca value at which the deformation becomes unsteady, leading to
153 the break-up of the bubble, is called the critical Capillary number (Ca_c). **Grace [1982]** conducted a
154 thorough experimental investigation on the deformation and the break-up of droplets accounting for
155 a wide range of viscosity ratios ($10^{-6} < \lambda < 10^3$) and found that Ca_c strongly depends on λ . Regarding
156 these phenomena, **Rumscheidt and Mason [1961]** distinguished the different deformation and break-
157 up mechanisms of droplets in shear flows, presenting three break-up modes. The first is a droplet-
158 breaking mode by the tips called *tip-streaming*. In the second case, the drop breaks by the *binary*
159 *break-up* mode, splitting into two daughter drops. In the third case, the drop extends to a long thread
160 that breaks after a long time. **Rumscheidt and Mason [1961]** concluded that λ is the most important
161 parameter determining the break-up type. **De Bruijn [1993]** analyzed the cause of *tip-streaming*:
162 interfacial tension gradients developed on the drops, resulting in a low interfacial tension at the tips
163 and a higher tension elsewhere. According to the author, this phenomenon occurs when there is a
164 moderate level of the SAA. Most of the results regarding break-up phenomena cited above are related
165 to drops and not bubbles; in this case λ is far smaller due to the low gas density. Furthermore, the role
166 of SAA such as proteins on single bubbles deformation and break-up has been poorly investigated.

167 It is commonly admitted for dry foams that their stability is strongly linked to the interfacial
168 properties of the adsorbed layers, in particular to their rheological properties, such as the surface
169 viscoelasticity of protein films on the one hand, or the Gibbs-Marangoni mechanism for low-
170 molecular-weight surfactants on the other hand. Their role on single bubbles deformation and break-
171 up in a liquid phase has, however, been poorly studied in comparison to single drops. Even though
172 these properties play obviously a key role in foaming properties from the laboratory scale to the
173 industrial scale, no quantitative approach has been able to link foaming efficiency and interfacial
174 properties up to now. From qualitative analysis, it is clear that if an enhanced interfacial rigidity may
175 be necessary to improve long-term foam stability, this should not prevent bubbles break-up during
176 foam formation. This means that the control of the respective dynamics of shear-induced bubble
177 break-up and interfacial mechanisms able to increase interface rigidity and stability is pivotal for to
178 a successful aeration process. While recent advances in interfacial rheological properties in the
179 nonlinear domain could help reach a better understanding [**Bykov et al., 2015**], experimental

180 techniques remain, however, limited to a too low-frequency domain in comparison to industrial
181 conditions.

182 Extensive literature can be found regarding protein-stabilized gas-liquid interfaces in foams
183 [Zhan et al., 2022] but it is also important to investigate the origins of the foamability of protein
184 solutions. Souidi et al. [2012] investigated the mechanisms of bubble break-up with food model
185 solutions containing whey proteins. *Tip-streaming* was identified as the main bubble break-up mode,
186 and this was associated with a narrow bubble size distribution in the foams obtained with this protein
187 solution in the range between 25 and 50% (v/v) gas fraction. These conclusions raised an important
188 question: is this break-up mode related to the specific operating conditions (i.e., shear flow in laminar
189 conditions at a low viscosity ratio) whatever the SAA, or is this break-up mode depends on the nature
190 of the SAA (i.e., whey proteins) used?

191
192 In order to answer these questions, this paper aims to study the deformation and break-up
193 mechanisms under shear flow of bubbles stabilized by three different SAA. Whey protein concentrate
194 (WPC), sodium caseinate (SCN), and tween 20 (TW20) were used in Newtonian model-solutions
195 with controlled bulk viscosity and at the same weight percentage. WPC and SCN have nearly the
196 same average molecular weight (14-25 kDa) but not the same structure: whey proteins are globular
197 proteins, whereas caseins have a flexible structure [Fox et al., 2017]. TW20 was selected as a low-
198 molecular-weight (LMW) surfactant to extend the range of SAA's type and molecular weight. The
199 three model-solutions were also used to carry out aeration with two different pilot-scale apparatus.
200 The objective was to investigate how the SAA affects single bubble break-up mode and to establish
201 a relationship between aeration and single bubble break-up data.

202 203 2. MATERIAL AND METHODS

204 205 2.1. Raw materials

206
207 In this study, model-fluids consisting of dehydrated glucose syrup and SAA were used to
208 tailor physicochemical properties (viscosity, surface properties) close to food media. The glucose-
209 dried powder (Glucidex IT21) used was obtained from *Roquette Frères* (France). Three different
210 SAA were used:

- 211 - Whey protein concentrate (WPC, Protarmor 80) was obtained from *Armor Proteins* (France). This
212 concentrate with a high nutritional value is assumed free of lactose and fat. WPC contains 85%
213 (w/w) protein material consisting of 75% β -lactoglobulin, 6% α -lactalbumin, and the rest as BSA
214 and immunoglobulins. It is used as a foaming agent in the production of abundant and stable
215 foams.
- 216 - Sodium caseinate (SCN) was also provided by *Armor Proteins* (France). SCN is a highly purified
217 caseinate protein (91% w/w) used in the food industry as an emulsifier and/or a stabilizer
218 [Einhorn-Stoll et al., 2002].
- 219 - Tween 20 (*Sigma-Aldrich Co.*, Germany) is a non-ionic surfactant based on aliphatic fatty acid
220 esters having a hydrophilic-lipophilic balance (HLB) of 16.7. In the food industry, Tween 20
221 (TW20) is mainly used in frozen cream. It is known to form dry foams and enhance the
222 stabilization of interfaces by steric forces [Samanta and Ghosh, 2011].

223
224 The model-fluids were prepared by dispersing 2% (w/w) SAA (WPC or SCN or TW20) in tap water
225 (34 to 38% w/w) using an electric mixer (2.5 L Stephan UMC 5, Germany) at 300 rpm and room

226 temperature. Then, glucose syrup powder (60 to 64% w/w) was added to the SAA solutions, the
227 mixture was homogenized at 1000 rpm for 30 minutes. Sodium azide NaN_3 (0.02% w/w) was finally
228 added to the solutions to prevent microbial activities. Once prepared, the solutions were stored at 4°C
229 for 48 hrs. for degassing and ensuring full hydration. After aging, they were characterized in terms of
230 density (ρ_i), rheological properties (η) and equilibrium surface tension (σ).
231

232 2.2. Characterization of the model-fluids

233

234 The density of the model-fluids was measured by filling a crystallizer (*Duran*) of known
235 volume; the whole was then weighed with a balance (*New Classic ML*, Mettler Toledo, Switzerland).
236 The same procedure was followed for foams density measurements.

237 Rheological measurements were performed using a stress-controlled rheometer (AR G2, *TA*
238 *instrument*, USA) equipped with a Peltier circulator for temperature control. Flow curves were
239 obtained by monitoring shear stress (τ) as a response from 0.1 to 1000 s^{-1} shear rate ($\dot{\gamma}$) ramp. All
240 tests were performed using a parallel-plate geometry (40 mm diameter; 1000 μm gap). The
241 temperature was maintained at 20°C during measurements. Newtonian model was applied.
242

243 The equilibrium surface tension of the prepared solutions was measured using a tensiometer
244 (K12, *Krüß GmbH*, Germany) equipped with a Wilhelmy platinum plate. The measurements were
245 performed at a constant temperature (20°C) without sample dilution. The measurements were adapted
246 to the SAA: 1 min for TW20 solution and at least 1 hr. for protein solutions.

247 All these measurements were done in triplicate and the average values are reported in [Table 1](#).

247 *Table 1: Physicochemical properties of the model-fluids.*

SAA	Viscosity (Pa.s)	Surface tension (mN/m)	Density (kg/m^3)
WPC	1.1 ± 0.1	50.4 ± 0.3	1280 ± 10
SCN	0.92 ± 0.03	55.4 ± 0.3	1360 ± 10
TW20	0.84 ± 0.06	35.2 ± 0.2	1350 ± 30

248

249 2.3. Continuous foaming apparatus and conditions

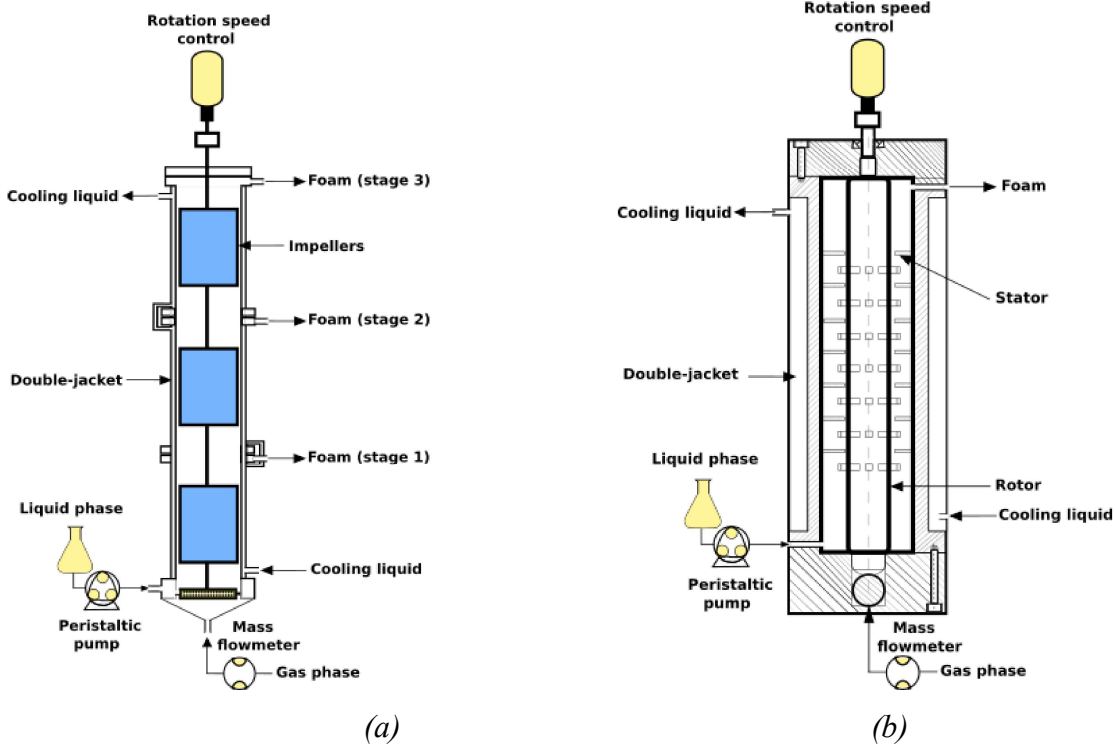
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251 Two types of continuous aeration devices were used to produce foams:

- 252 - a Narrow Angular Gap Unit (NAGU) consisting of a 3 stage-jacketed cylindrical stainless-steel
253 column of 35 mm diameter ([Fig. 1a](#)). Each stage is mechanically stirred using seven right-angle
254 mixing elements of 33 mm diameter. The compact and shifted configuration of the impellers was
255 used to achieve efficient gas incorporation [[Souidi et al., 2012](#)].
- 256 - a Rotor-Stator (RS) consisting of a 35 mm diameter stator and a 15 mm diameter rotor, both fitted
257 with seven rows of squared pins of 7.5 mm length resulting in a pin-to-wall gap of 2.5 mm ([Fig.](#)
258 [1b](#)). This geometry corresponds to the scale-down of typical aeration equipment of the food
259 industry.

260 More details can be found in [Narchi et al. \[2011\]](#).

261



262
263

264 *Figure 1: Schematic description of the experimental setups. (a) Narrow angular gap unit (NAGU)*
265 *(b) Rotor-Stator (RS).*

266 The liquid phase was supplied using a peristaltic pump (Masterflex L/S, Cole-Parmer Instr.
267 Co., USA) and the gas phase was supplied by a mass flow controller (*Emerson Brooks Inst.*, USA) in
268 standard temperature and pressure (STP) conditions. Liquid was introduced by a side inlet in both
269 devices, while gas was introduced through a sinter plate in NAGU and laterally in RS without sinter
270 due to the configuration of the device. The impeller rotation speed (N) could vary from 10 to 1200
271 rpm using a speed-controlled motor (Janke Kunkel RE 16, *Ika-Werke GmbH*, Germany). Experiments
272 were carried out at atmospheric pressure and the temperature was maintained at 20 °C. Steady-state
273 conditions were achieved when the foam density value remained constant for three successive
274 measurements.

275 In both devices, the reference gas (G_i) and liquid (L_i) volumetric flow rates were set at 10
276 mL/min and 30 mL/min respectively. The maximum theoretical gas fraction ε_{max} is 25% (v/v) (Eq.
277 6), which had been shown to be an adequate gas fraction for optimal gas dispersion [Narchi et al.,
278 2011].

279

$$280 \quad \varepsilon_{max} = \frac{G_i}{G_i + L_i} \quad (6)$$

281

282 Foaming efficiency is then calculated by dividing the actual gas fraction to its maximum value:

283

$$284 \quad \text{Foaming efficiency} = \frac{\varepsilon}{\varepsilon_{max}} \quad (7)$$

285

286 Foam gas volume fraction (ε) was calculated using the density of the model-fluid and foam (ρ_i and
287 ρ_f):

288

289
$$\varepsilon = \frac{\rho_i - \rho_f}{\rho_i} \quad (8)$$

290
 291 Online image analysis consisting of a CCD camera coupled to a microscope (Axiovert-25, *Carl Zeiss*
 292 *Jena GmbH*, Germany) was used to measure bubble size distribution. Images were processed by free
 293 software *ImageJ* to determine bubble size. At least 500 bubbles were analyzed to avoid statistical bias
 294 and average bubble size was expressed considering the average diameter (D_{mean}) (Eq. 9) with n the
 295 number of bubbles and D_i the individual bubble diameter:

296
$$D_{mean} = \frac{\sum_{i=1}^n D_i}{n} \quad (9)$$

297
 298 The effect of residence time inside the foaming devices was also assessed. For NAGU, it was
 299 possible by taking samples at the end of each stage. Concerning RS, volumetric flow rate conditions
 300 were reduced to $G_i = 3.3$ and $L_i = 10$ mL/min to increase residence time by a factor 3. Table 2
 301 summarizes the process parameters related to flow conditions and rotation speed in both devices.
 302

303 *Table 2: Main characteristics of the two foaming devices.*

Parameters	NAGU	RS
Maximum shear rate $\dot{\gamma}_{max}$ (s ⁻¹) at 1200 rpm*	2200	880
Volume mean shear rate $\dot{\gamma}_{mean}$ (s ⁻¹) at 1200 rpm**	386	364
Residence time (\bar{t}) (s) - 1 stage; $G_i/L_i = 10/30$ ***	188	270
Residence time (\bar{t}) (s) - 3 stages; $G_i/L_i = 10/30$	564	-
Residence time (\bar{t}) (s) - 1 stage; $G_i/L_i = 3.3/10$	-	812

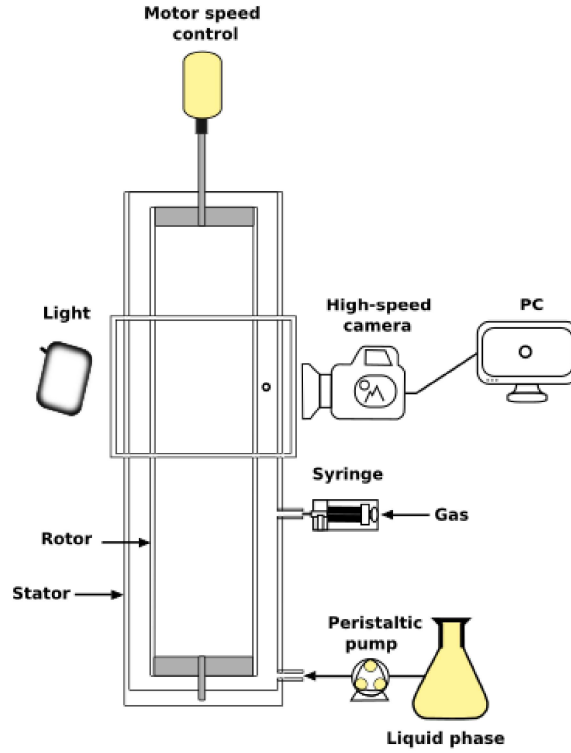
304 *Maximum shear rate is calculated with the Couette approximation

305 **Volume mean shear rate is calculated with the Metzner and Otto approximation

306 *** Residence time considered as the reference

307 308 2.4. Single-bubble visualization

309
 310 The visualization system (Fig. 2) is a transparent Couette device developed by [Souidi et al.](#)
 311 [2012]. It consists of 35 mm diameter cylinder as a stator and an inner cylinder of 31 mm diameter
 312 (as a rotor). The model-solutions were filled in the remaining 2 mm gap ($e_{Couette}$) between the two
 313 cylinders, then gas bubbles were inserted from a syringe (*Hamilton Company*, USA) connected to a
 314 180 mm (internal diameter) capillary tube (*Postnova Analytics GmbH*, Germany). The gas volumetric
 315 flow rate was controlled by a syringe pump (*KD scientific*, USA). A squared shape transparent box
 316 filled with the model-solution was added to prevent optical distortion. The entire device was
 317 illuminated by a continuous light source of 15 W (SBACK II, *TPL Vision*, France) to provide good
 318 recording conditions with a CMOS camera (*Omron Senntech Co*, Japan). Sequences were recorded
 319 at 300 frames/s and treated using *Dyva* software (*Alliance Vision*, France).



321

322 *Figure 2: Illustration of the transparent Couette system: side view.*

323

324 Images of undeformed bubbles were realized to determine the initial bubble diameter, which
 325 remained between 300 and 900 μm , ($0.15e_{\text{Couette}}$ to $0.45e_{\text{Couette}}$) in order to prevent border effect due
 326 to the cylinder walls. Next the video recordings were realized at different rotation speeds to analyze
 327 bubble deformation and determine the minimum value of shear rate needed to achieve break-up with
 328 a given bubble size. Shear rate $\dot{\gamma}$ is estimated by the Couette approximation where R_i is the radius of
 329 the inner cylinder and N its rotation speed:

330

331

$$\dot{\gamma} = \frac{2 \pi R_i N}{e_{\text{couette}}} \quad (10)$$

332

333 In a second time, to better understand the nature of bubble division, the internal cylinder was
 334 replaced by a transparent impeller, close to that of NAGU, but of 35 mm diameter, so that the
 335 maximum shear rate was still provided by Eq. (10), but with flow conditions closer to aeration
 336 process.

337

338 **3. RESULTS**

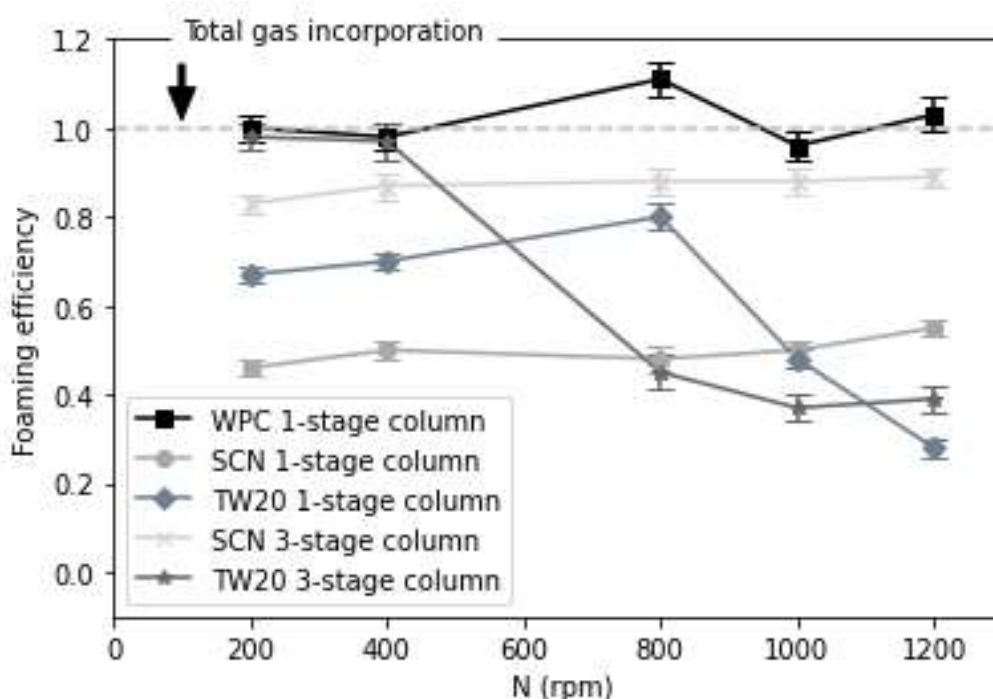
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340 **3.1. Foaming performances in the stainless steel NAGU**

341

342 Fig. 3 displays *foaming efficiency* for each SAA model-solution in 1- and 3-stage NAGU. It
 343 emerges that WPC solution was the only one reaching full gas incorporation from 200 to 1200 rpm,
 344 with only 1-stage column. Consequently, no significant effect of rotation speed was observed with
 345 this SAA. When replacing WPC with SCN, foaming efficiency reached at most 55% ($N=1200$ rpm)
 346 with the 1-stage column, while *foaming efficiency* increased to 89% ($N=1200$ rpm) at 3-stage column;

347 in both cases, efficiency was independent of N . This increase suggests that one could achieve full gas
 348 incorporation by further increasing the foam residence time in the column, i.e., by reducing gas and
 349 liquid flow rates or adding an additional stage. With TW20 as SAA, maximum foaming efficiency
 350 reached 80% at 800 rpm for 1-stage column; this value decreased with increasing N and reached 28%
 351 at 1200 rpm. When the whole column was used (three stages), foaming efficiency was improved and
 352 reached 98% at 200 rpm; but this value decreased when N was increased and reached 39% at 1200
 353 rpm. Rotation speed increase acted as a centrifugation effect promoting phase separation and/or
 354 coalescence of large bubbles instead of enhancing foam formation, as shear and elongation forces
 355 increase with N . Similar observation had also been reported with Tween 80 [Narchi et al., 2007],
 356 another LMW surfactant structurally close to Tween 20. It clearly appears from these results that both
 357 SAA families (protein and LMW surfactant) act differently regarding gas dispersion even using the
 358 same operating conditions.
 359



360

Figure 3: Foaming efficiency as a function of the rotation speed for WPC, SCN, and TW20. Experiments carried out with NAGU.

361

362 A comparison of bubble sizes as a function of rotation speed is displayed in Table 3. With the
 363 reference residence time (1-stage column), SCN- and TW20-stabilized bubbles were bigger than
 364 those stabilized by WPC. Mean diameter was nearly the same, whatever the rotation speed for WPC,
 365 whereas bubble size decreased when N increased with SCN and TW20 solutions. This latter trend
 366 had been widely reported in the literature for different foaming devices [Jabarkhyl et al., 2020; Badve,
 367 2020; Mary et al., 2013]. Increasing N resulted in higher shear stress inside the column, inducing the
 368 break-up of larger bubbles into smaller ones, but it also led to more uniform and narrower bubble size
 369 distribution (data not shown). When residence time was increased by adding two more stages, SCN-
 370 and TW20-stabilized bubble size were close to those of bubbles stabilized by WPC at 1-column stage
 371 (10-20 μm), which seems to be the minimum size achievable with this device. The sensitivity to the
 372 increase in N became much less important than at 1-stage column. Regarding standard deviation, it
 373 also decreased considerably for SCN and TW20.

374

375

376 *Table 3: Bubble mean diameter (D_{mean}) and standard deviation (SD). Experiments performed with*
 377 *NAGU at 1- and 3-stage column.*

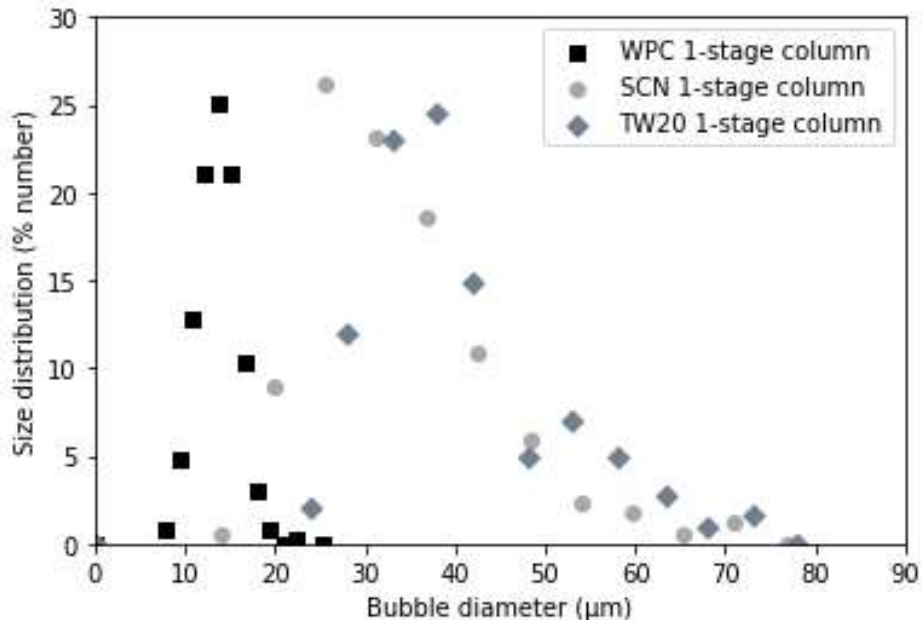
N (rpm)	$D_{mean} \pm SD$ (μm)			$D_{mean} \pm SD$ (μm)	
	1-stage column ($\bar{t} = 188$ s)			3-stage column ($\bar{t} = 564$ s)	
	WPC	SCN	TW20	SCN	TW20
200	17 ± 4	50 ± 30	50 ± 40	15 ± 6	20 ± 9
400	17 ± 4	50 ± 20	50 ± 40	13 ± 4	19 ± 7
800	17 ± 4	40 ± 20	40 ± 20	11 ± 3	16 ± 5
1000	15 ± 4	40 ± 20	40 ± 20	11 ± 3	14 ± 7
1200	14 ± 3	30 ± 10	30 ± 20	12 ± 4	13 ± 6

378

379 This latter result is confirmed by observing bubble size distribution (BSD) reported in Fig. 4. A
 380 unimodal profile was observed at 1-stage column with WPC. BSD was larger and rather bimodal with
 381 SCN and TW20 solutions. When residence time was increased (Fig. 4b), BSD became nearly
 382 unimodal for SCN and TW20, which was also consistent with the reduction in the standard deviation.
 383 It must be mentioned that BSD for foams stabilized by SCN and TW20 only includes bubbles
 384 successfully dispersed within the foaming device, while big gas plugs observed when the efficiency
 385 was less than 1 were excluded. A conclusion can be that if primary bubbles started to be split, they
 386 could be reduced by serial break-up to small bubbles, especially with longer residence times, whereas
 387 bubbles that did not undergo dispersion formed gas pockets.

388

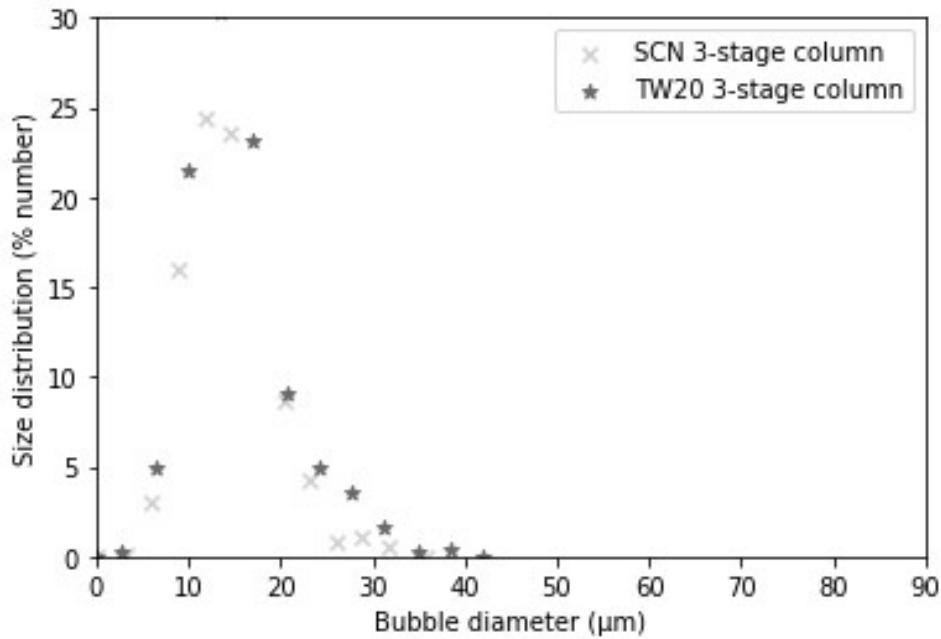
389



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(a)



(b)

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393

394 *Figure 4: Effect of surface-active agents on bubble size distribution. Results for $N = 1200$ rpm in (a)*
395 *1 and (b) 3-stage column.*

396

3.2. Foaming performance in the RS

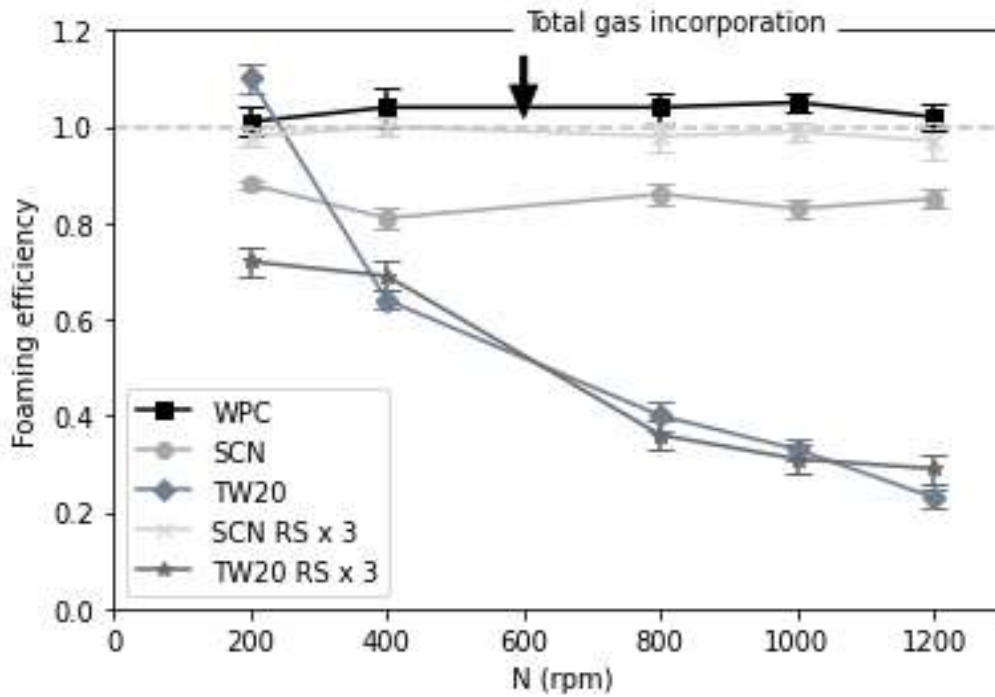
397
398

399 To confirm the results obtained with the NAGU device, the residence time's effect was also
400 studied on foaming operation using the RS device. Aeration was first carried out with the flow rates
401 $G_i = 10$ and $L_i = 30$ mL/min. WPC solution reached maximum efficiency, whatever N , while SCN
402 solution achieved at most 90% efficiency (Fig. 5). Increase in residence time by a factor 3 led to a
403 total gas incorporation with the SCN solution. This differed from the NAGU device for which this
404 residence time increase was not high enough to incorporate all the gas. This could be explained by
405 the fact that the residence time with the RS at flow rates $G_i = 3.3$ and $L_i = 10$ mL was greater than
406 with the NAGU at flow rates $G_i = 10$ and $L_i = 30$ mL (Table 2). As with NAGU, the efficiency seems
407 independent of N in RS with SCN and WPC solutions. With the TW20 solution for the smallest
408 residence time, 100% efficiency was achieved at 200 rpm; then, it decreased when increasing N down
409 to 23% at 1200 rpm. In addition, increase in residence time did not lead to a better foaming efficiency,
410 and this rise did not change the sensitivity of foaming efficiency to the increase in N . It can be deduced
411 that this negative dependence of *foaming efficiency* on N seems to be a characteristic of TW20
412 solution, which is consistent with the observations and conclusions obtained in NAGU experiments.

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Figure 5: Foaming efficiency as function of the rotation speed. Experiments carried out with RS. “RS x 3” denotes the residence time’s increase by 3 times ($G_i = 3.3$ and $L_i = 10$ mL/min).

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Regarding bubble size and BSD, Table 4 shows that the RS device produced bigger bubbles than the NAGU, especially at low rotation speed. This difference decreased as N increased. Bubbles reached their minimum diameter when N exceeded a threshold speed which was around 800-1000 rpm. It should be pointed out that the axial distance available for the fluids (gap) is smaller in the NAGU (1 mm) than in the RS (2.5 mm). Therefore, the maximum shear rate is greater in the NAGU than in the RS; this explains why the NAGU allowed obtaining smaller bubbles than the RS especially for WPC. Residence time increase from 270 s to 812 s allowed a reduction in bubble size whatever the SAA (Table 4). This impact was significant at low rotation speed, but almost insignificant above 800 rpm.

428

429

Table 4: Bubble mean diameter (D_{mean}) and standard deviation (SD). Experiments performed with the RS device, with $\bar{t} = 270$ s and $\bar{t} = 812$ s.

N (rpm)	$D_{mean} \pm SD$ (μm) $\bar{t} = 270$ s			$D_{mean} \pm SD$ (μm) $\bar{t} = 812$ s	
	WPC	SCN	TW20	SCN	TW20
200	50 ± 20	50 ± 20	90 ± 80	27 ± 8	30 ± 20
400	40 ± 20	21 ± 7	50 ± 20	20 ± 8	30 ± 10
800	40 ± 20	14 ± 5	30 ± 20	16 ± 5	21 ± 9
1000	40 ± 10	14 ± 5	30 ± 20	15 ± 5	22 ± 9
1200	28 ± 7	14 ± 4	20 ± 20	14 ± 5	22 ± 9

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433 3.3. Single bubble deformation and break-up

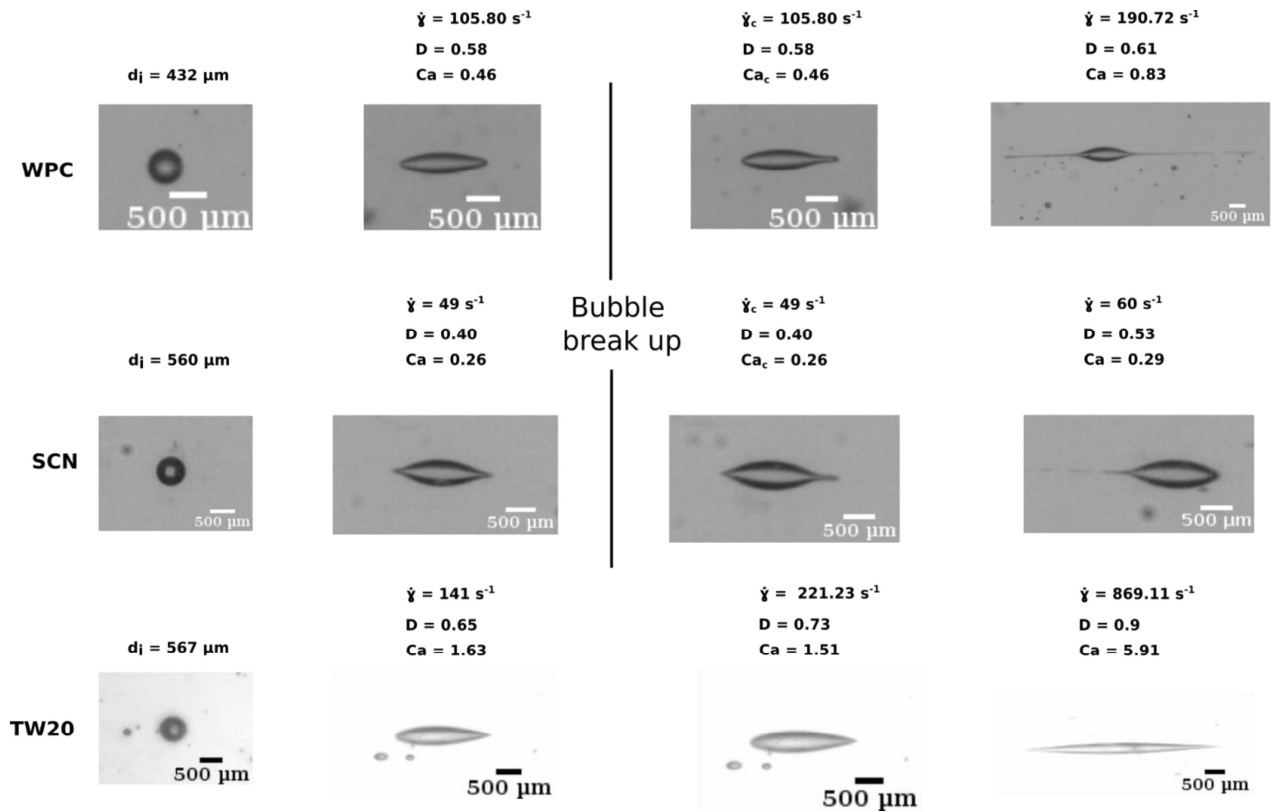
434

435 Bubble deformation and break-up were observed in the transparent Couette device. The three
436 same SAA solutions (WPC, SCN, and TW20) were used for this study. During the experiments, air
437 bubbles were generated in the solutions, a steady shear was applied, and the deformation (D for $Ca <$
438 1 and L/a for $Ca > 1$) was calculated from image analysis. Fig. 6 shows the development of bubble
439 deformation in simple shear flow in the transparent Couette device. For each SAA, the first frame
440 displays an initial bubble without shear stress: bubbles were thus assumed to be spherical in shape.
441 Under the action of a constant shear flow, these bubbles initially at rest immersed in the model
442 solution progressively deformed; after a transient time, it reached a steady state as long as conditions
443 remained the same (Fig. 6 from frame 2). Regardless of the SAA used, raising shear rate induced an
444 increase in deformation.

445 For protein-stabilized bubbles, deformation increase led to a break-up by *tip-streaming* (Fig. 6
446 frame 3 for WPC and SCN). This is a break-up mode in which a stream of tiny bubbles is ruptured
447 off the tips of the bubble. This mode takes place randomly on the front or at the back of the bubble.
448 At this stage, shear rate value was determined and used to calculate the critical Capillary number Ca_c
449 from Eq.1. Observations also showed that beyond Ca_c , a filament appeared on both sides of the
450 bubble, and the higher the shear rate, the longer this filament. This eventually led to a serial break-up
451 and the release of tiny bubbles in a *jetting mode* (Fig. 6 frame 4 for WPC and SCN) as observed in
452 microfluidic systems [Montanero and Gañán-Calvo, 2020]. In addition, the releasing frequency of
453 daughter-bubbles with this break-up mode was higher than in the case of a simple *tip-streaming* and
454 the released-bubbles were smaller.

455 Like bubbles stabilized by proteins, as the shear rate was increased, TW20-stabilized bubbles
456 became thinner and longer. However, shear rate values which led to the rupture of bubbles stabilized
457 by proteins did not induce break-up with TW20-stabilized bubbles. They continued deforming and
458 lengthening as shear rate increased (Fig. 6 frame 2-4 for TW20).

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461

462 *Figure 6: Air bubble initial shape, then deformed, and break-up (only for protein-stabilized bubbles)*
 463 *in simple shear flow (Couette device, scale on each frame). The applied shear rate is increased from*
 464 *the left to right (frame 1 to frame 4). The viscosity ratio λ is between $1.68 \cdot 10^{-5}$ and $2.20 \cdot 10^{-5}$, and the*
 465 *scale's marks on each frame corresponds to $500 \mu\text{m}$.*

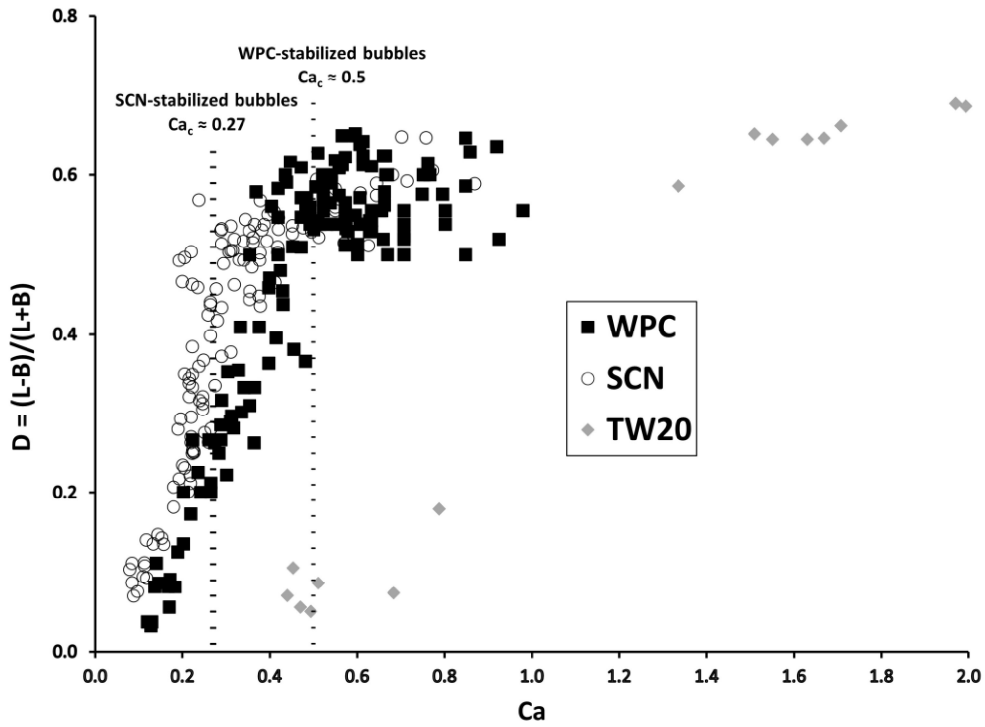
466

467 As described, qualitative analysis with the proteins (WPC and SCN) showed similar bubbles
 468 behaviors. However, significant differences were observed in quantitative data. To examine the
 469 relationships between bubble deformation and Capillary number, bubble deformation parameter D of
 470 the bubbles vs. Ca was plotted on Fig. 7a. Experimental data displayed that for $Ca \leq 0.5$, D scaled
 471 with Ca , and bubbles were nearly spherical. This relationship was first observed with droplets by
 472 Taylor [1934] for small deformations ($Ca \ll 1$). Furthermore, as shown in Fig. 7a, SCN-stabilized
 473 bubbles deformed more than WPC-stabilized bubbles, leading to a smaller critical Capillary number
 474 Ca_c . In fact, bubbles stabilized with SCN broke for $Ca = 0.27$, while those stabilized with WPC broke
 475 for $Ca = 0.5$. Above these values, D remained constant around 0.5-0.6.

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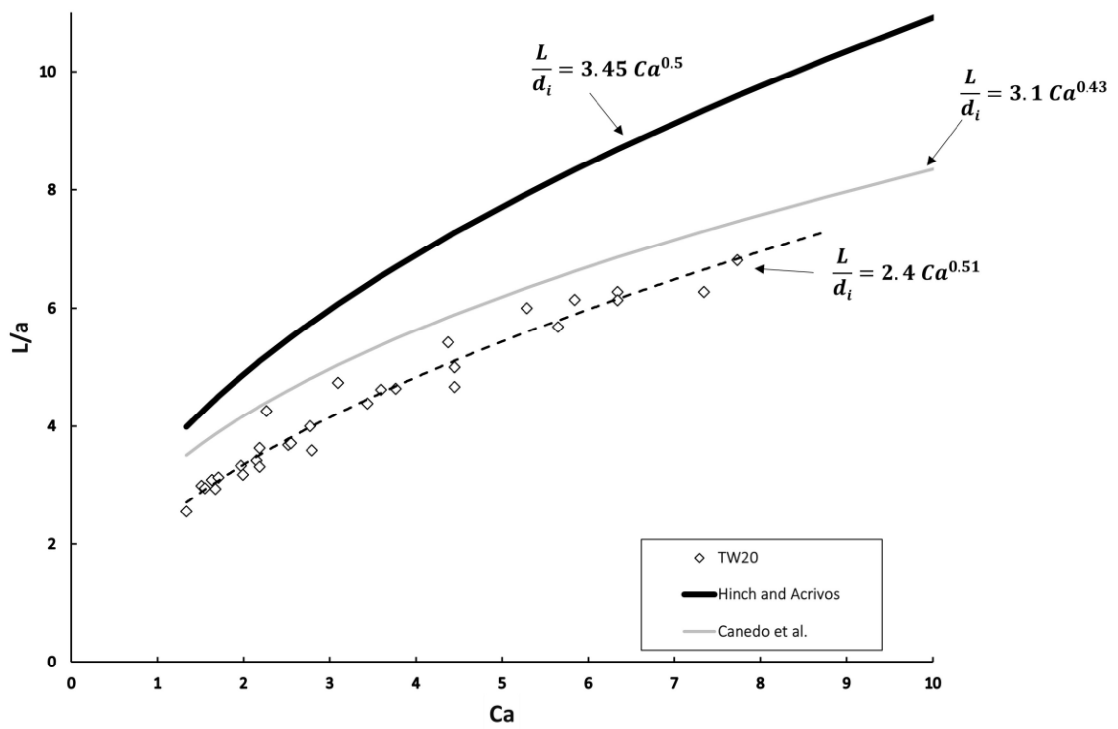
477 Regarding bubbles stabilized by TW20 for $Ca < 1$ (Fig. 7a), they deformed less than protein-
 478 stabilized bubbles, and in the end, as said before, they did not break. To reach the same deformation
 479 degree as bubbles stabilized by proteins, Ca values higher than 1 were necessary. For Ca values from
 480 1 to 5, D increased from 0.6 to 0.9 (data not shown). At these high deformations ($Ca > 1$) the
 481 parameter L/a is commonly used to describe the deformation degree. Fig. 7b presents a plot of this
 482 parameter as a function of Ca . Experimental results are compared to the theoretical predictions of
 483 Hinch and Acrivos [1979] (Eq.4) and to the experimental results of Canedo et al. [1993] (Eq.5). Power
 484 law models (Eq. 3) fitting the data were reported in the figure for the three cases. For TW20 solution,
 485 experimental data seems to follow the same trend of the literature. The values of the constant α appear
 486 to be in the same order of magnitude, while those of β differ slightly. Remarkably, experimental
 results are close to those of Canedo et al. [1993] where SAA were not used, but the equilibrium

487 surface tension of their solution was around 33-41, notably close to that of TW20 solution, as if this
488 parameter was important regarding large deformation.
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(a)

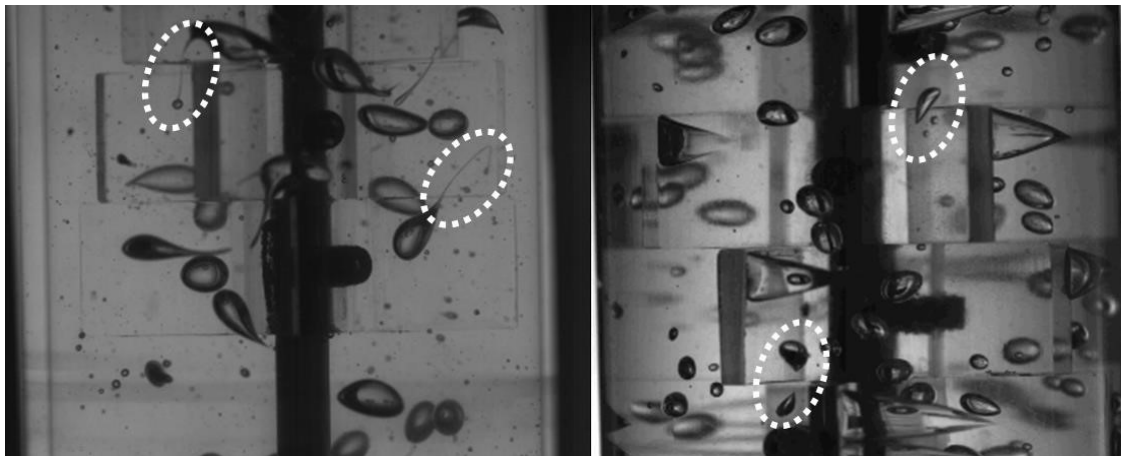


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(b)

497 Figure 7: (a) Deformation parameter D as a function of the Capillary number Ca for bubbles
498 stabilized by proteins and surfactant agents in simple shear flow; (b) Deformation parameter L/a as
499 a function of the Capillary number Ca for bubbles stabilized by Tween 20 in simple shear flow.
500 Symbols represent measured values, and the dashed line is to guide the eye. The solid thick line is the
501 prediction by *Hinch and Acrivos [1979]* based on slender body theory. The thin grey line refers to
502 the model prediction by *Canedo et al. [1993]*.
503

504 Even though the TW20 model-solution did not allow a full gas incorporation in aeration
505 process, a fraction of the gas was incorporated; this means that bubble break-up took place in the
506 apparatus anyway. To better understand the nature of bubble division, the Couette device internal
507 cylinder was replaced by a transparent impeller. This setup was used to analyze qualitatively bubble
508 break-up phenomena in dispersion conditions with WPC, SCN, and TW20 solutions (Fig. 8). Under
509 the same operating conditions, break-up by the bubble tip with a single or multiple daughter bubble
510 seemed to be the main break-up mode for bubbles stabilized by WPC (Fig. 8a), and this confirms the
511 results obtained previously. The same observation was made with SCN (data not shown). Using
512 TW20 as SAA, either no break-up was observed as in the Couette device, or a new break-up mode
513 appeared. It was a total break-up in which the central part of the bubble formed a neck in the middle
514 that progressively thinned, and finally, the bubble splits into two main daughter-bubbles in a binary
515 break-up mode, forming also small satellite bubbles in between (Fig. 8b). This break-up mode had
516 already been reported in microfluidic systems with junctions [Fu et al., 2011]. It was also observed
517 in the foaming device (NAGU) between two successive mixing elements. Actually, bubbles were torn
518 between two depression areas at the back of the paddles in a Venturi effect. In this case, break-up was
519 not a consequence of pure shear but rather of an elongational flow.
520



521
522

523 (a) (b)

524 Figure 8: Bubble break-up mechanism (white dashed line) under given rotational speed (200 rpm):
525 (a) tip-break-up with WPC and (b) absence or total break-up with TW20.

526 These results highlight the qualitative and quantitative differences between the three SAA at bubble
527 scale. The observed differences are related to the break-up threshold, but also to the break-up mode,
528 and they can be a way to better understand the pilot-scale results.
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532 4. DISCUSSION

533

534 In the previous section, experimental results indicated that: (1) foam production was more
535 efficient with WPC compared to SCN and TW20; (2) bubbles coated by WPC and SCN broke by *tip-*
536 *streaming* at low shear rate and a smaller Ca was required for SCN-stabilized bubbles than for those
537 stabilized by WPC; (3) TW20-stabilized bubbles did not break even at higher shear rate or broke by
538 the binary break-up mode. These results underline the differences in the behavior of SAA at the
539 bubble interface leading to a different foaming result. [Souidi et al. \[2012\]](#) already tried to establish a
540 direct link between a single bubble break-up experiment and pilot-scale foaming results with WPI
541 (whey protein isolate). Since *tip-streaming* requires a lower shear rate [[Grace, 1982](#)], bubble rupture
542 was facilitated by this mode, and BSD was narrower. This observation can be extended to SCN even
543 though break-up thresholds were different. On the other hand, the lack of tip-break-up with TW20
544 seems to lead to poor foaming results.

545 As shown in [Table 1](#), the SAA's nature strongly influences the equilibrium surface tension
546 ($\sigma_{sc} = 55.4$, $\sigma_{WPC} = 50.4$, and $\sigma_{TW20} = 35.2$ mN/m). Even though TW20 allowed a greater reduction in
547 equilibrium surface tension than proteins, it did not enhance gas dispersion compared to proteins, as
548 it can be deduced from the pilot-scale results. Thus, considering only the absolute value of equilibrium
549 surface tension (σ) is not consistent with the break-up processes once a bubble is submitted to shear
550 flow. Moreover, the three solutions almost had the same viscosity and experiments were performed
551 under the same operating conditions. Therefore, the absence (TW20) or presence (WPC, SCN) of tip-
552 break-up phenomena could not only be attributed to the laminar flow and/or to the low viscosity ratio,
553 but likely to the way these SAA stabilized interfaces. It is then more relevant to consider the local
554 and/or dynamic surface tension which is influenced by the SAA surface coverage during foam
555 formation.

556 *Tip-streaming* was mainly attributed to an interfacial tension gradient due to the presence of
557 surfactants, resulting in reduced interfacial tension at the tips as proposed by [de Bruijn \[1993\]](#) and
558 [Eggleton et al. \[1999\]](#) who worked on drops. In the case of bubbles, to reach this surface tension
559 gradient, the surfactants must (i) migrate from the bulk to the interface, (ii) adsorb to the interface,
560 and (iii) convey during deformation towards the bubble ends, which results in large tip stretching.

561

562 LMW emulsifiers, such as TW20, stabilize bubbles in the short range through the Gibbs-
563 Marangoni mechanism acting in the tangential direction and opposite to the direction in which the
564 surfactants are pushed by the flow [[Moyle et al., 2012](#)]. In fact, bubbles are stabilized by a mobile
565 monomolecular layer with low surface viscoelasticity, in which rapid diffusion within the surface
566 layer and exchange with the bulk solution occur [[Mackie and Wilde; 2005](#)]. This relies on the
567 surfactants which rapidly migrate to regions of the interface depleted of surfactant because of
568 deformation. This could be an explanation for the different deformation behaviors observed with
569 proteins (SCN and WPC) and TW20: TW20 seems to have a better ability to migrate and adsorb at
570 the interface than proteins, preventing the accumulation at the tips even at a very high shear rate. It
571 should also be mentioned that although the mass percent of SAA in the solutions is the same (2%),
572 the number of molecules in the solutions is not equivalent due to the structural and molecular weight
573 differences of these two SAA families. In addition, [Miller et al. \[2005\]](#) reported that proteins
574 desorption rate, such as β -lactoglobulin and β -casein, is 10^4 to 10^8 times slower than that of
575 conventional surfactants. Therefore, desorption in the case of TW20 could also limit the SAA
576 concentration gradient. The matter comes down to the comparison between two characteristic times:
577 the first is the SAA accumulation's time at the tips induced by shear stress; the second is the migration

578 time either from the bulk to the free interface created or the desorption time from the interface.
579 Considering the differences between TW20 and proteins, these characteristic times should be shorter
580 for TW20. Moreover, with surfactants, the Marangoni effect could also curb the deformation.
581 Consequently, much higher shear stress would be required with TW20 to get tip-break-up in shear
582 flow [Abbassi-Sourki et al., 2012]. An approximate value for this shear rate could be calculated using
583 the results from Grace [1982] on droplets in simple shear flow. The extrapolation suggests that
584 bubbles should break by binary break-up mode for $Ca_c \approx 60$ when $\lambda = 2.2 \cdot 10^{-5}$, corresponding to a shear
585 rate around 2400 s^{-1} . As shown in Table 2, this value is out of reach with the devices used for aeration
586 and, nonetheless, bubble mean diameter (Table 3 and 4) is slightly superior with TW20 compared to
587 proteins, suggesting the occurrence of break-up. As Grace's work [1982] involved droplets and not
588 bubbles, the calculated shear rate value (2400 s^{-1}) is probably overestimated. In addition, Ca_c
589 proposed by Grace [1982] at a low viscosity ratio was not obtained for tip-break-up. In this study,
590 tip-break-up was also likely to occur with TW20 at a rather high shear rate, but other break-up
591 phenomena requiring lower power input may also occur, as observed in Fig. 8. As was simulated by
592 Mardaru et al. [2012] with the NAGU device and by Wu et al. [2014] with a RS device, flows
593 generated by aeration devices are complex, offering the possibilities for various break-up modes, so
594 that, rupture by tip-break-up does not seem to be the prevailing break-up mode with TW20, in contrast
595 to WPC and SCN.

596
597 Bubbles stabilized by WPC and SCN broke by *tip-streaming*, which led to the formation of
598 small bubbles with a narrow BSD, as observed during aeration operations with protein solutions.
599 There is, however, an important matter to discuss: is tip-break-up at low shear rate specific to the
600 presence of HMW surfactants such as proteins? According to de Bruijn [1993], *tip-streaming* neither
601 occurs at extremely low surfactant concentration, nor at high level where bubble coverage by
602 surfactant is guaranteed. But in the Couette device experiments, the second condition is fulfilled (2%
603 w/w) and this rupture mode was, nevertheless observed. In addition, Müller-Fischer et al. [2008]
604 observed bubble break-up by *tip-streaming* in glucose syrup solutions without any SAA and
605 concluded that tip-break-up occurred preferentially for bubbles even if there was no surface tension
606 gradient. All this data supports the idea that the understanding of bubble break-up mechanisms is far
607 from complete, but the present results tend to associate the use of proteins under laminar conditions
608 in food aeration to *tip-streaming*.

609
610 Regarding the break-up threshold, SCN- and WPC-stabilized bubbles broke around $Ca_c \approx 0.27$,
611 and $Ca_c \approx 0.5$, respectively. This difference in threshold could be explained by the viscoelasticity of
612 the layers formed around bubbles by these different protein types. The viscoelastic character of the
613 films formed by sodium caseinates, and whey proteins was analyzed in the literature: it appears that
614 the viscoelasticity of caseinate-adsorbed films was lower than that of WPC-adsorbed films [Cicuta,
615 2007; Álvarez Gómez and Patino, 2007]. According to these papers, interfacial layers formed by
616 globular proteins tend to be more viscoelastic than those formed by flexible, random-coil proteins,
617 such as β -casein. Then, the higher viscoelastic character of WPC-adsorbed layers seems to make
618 bubble surface less prone to deformation and rupture under shear stresses, which agrees with the
619 higher value of Ca_c obtained with WPC compared to SCN. It could, thus, be expected a better foaming
620 efficiency at pilot-scale with SCN but the contrary was observed. How could this be explained?
621 Efficiency and final BSD obtained after a foaming process is a result of a dynamic equilibrium
622 between bubble break-up and coalescence phenomena [Séguineau de Préval et al., 2014]. The
623 question is, therefore, to know whether SCN-stabilized bubbles were subjected to coalescence

624 phenomena. Due to the geometry of the aeration devices used, observing coalescence dynamics inside
625 the devices was not possible. There is, nonetheless, one argument against the coalescence hypothesis:
626 with SCN solution, foaming efficiency was raised to 100% by increasing residence time. That does
627 not mean that coalescence was absent in these experiments but in the context of aerated food with
628 $\varepsilon=25\%$, contact between bubbles is limited. Another reason could justify why SCN did not achieve
629 maximum efficiency during aeration: bubble surface coverage. During the visualization of single
630 bubble deformation, SCN concentration (2% w/w) was not a limitation to bubble break-up at low Ca
631 since only few bubbles were generated in a large amount of solution ($\varepsilon<1\%$). Therefore, there were
632 enough available SAA's molecules to cover the bubble surface and achieve bubble break-up. In the
633 case of aeration, surface area was increased by gas incorporation under mechanical stirring. As a
634 result, the amount of protein molecules needed to cover the bubble surface raised steeply at pilot
635 scale. If this protein amount is locally not sufficient, it may impact bubble deformation and break-up
636 mechanisms. The problem, however, is not only related to the number of molecules needed at
637 air/water interface, but also to the time necessary for them to migrate from the bulk to the interface
638 by diffusional transport. A higher residence time led, thus, to a better casein molecule availability, so
639 that, increase in residence time could induce a total gas incorporation using RS, even if it meant a
640 slower production rate.

641

642 5. CONCLUSION

643

644 A comparative experimental study dealing with food aeration at pilot scale and the
645 visualization of bubble deformation and break-up with three different SAA was conducted. The
646 air/water interface behaviors strongly depended on SAA when submitted to shear flows. Proteins, as
647 HMW SAA, promoted tip-streaming as the major break-up phenomenon due to local surface tension
648 gradients. Break-up thresholds differed between proteins because they acted differently at air/water
649 interface. TW20 as a LMW SAA, on the other hand, did not favor bubble break-up by simple shear
650 flow and needed either high shear or more complex flows to split bubbles. These observations
651 provided interesting insights to understand the macroscopic results on food aeration but could not
652 explain the kinetically governed differences reported between proteins.

653 Gathering information on the way surface-active agents migrate towards and adsorb
654 dynamically to bubbles surface, coupled to bubble deformation and break-up visualization under
655 different types of flows seems, therefore, a promising approach to better understand foam generation
656 and to reach the long-term goal of predicting the achievement of aeration operations.

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676

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678 **Kaies Souidi:** Investigation, Formal Analysis, Software, Data analysis. **Alain Marcati:**

679 Conceptualization, Methodology, Validation, Supervision, Writing - review & editing. **Christophe**

680 **Vial:** Conceptualization, Methodology, Validation, Supervision, Writing - review & editing.

681

682 **Declaration of Competing Interest**

683

684 The authors declare that they have no known competing financial interests or personal relationships
685 that could have appeared to influence the work reported in this paper.

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899

900 **Tables**901 *Table 1: Physicochemical properties of the model-fluids.*

SAA	Viscosity (Pa.s)	Surface tension (mN/m)	Density (kg/m ³)
WPC	1.1 ± 0.1	50.4 ± 0.3	1280 ± 10
SCN	0.92 ± 0.03	55.4 ± 0.3	1360 ± 10
TW20	0.84 ± 0.06	35.2 ± 0.2	1350 ± 30

902

903 *Table 2: Main characteristics of the two foaming devices.*

Parameters	NAGU	RS
Maximum shear rate $\dot{\gamma}_{\max}$ (s ⁻¹) at 1200 rpm*	2200	880
Volume mean shear rate $\dot{\gamma}_{\text{mean}}$ (s ⁻¹) at 1200 rpm**	386	364
Residence time (\bar{t}) (s) - 1 stage; $G_i/L_i = 10/30$ ***	188	270
Residence time (\bar{t}) (s) - 3 stages; $G_i/L_i = 10/30$	564	-
Residence time (\bar{t}) (s) - 1 stage; $G_i/L_i = 3.3/10$	-	812

904 *Maximum shear rate is calculated with the Couette approximation

905 **Volume mean shear rate is calculated with the Metzner and Otto approximation

906 *** Residence time considered as the reference

907

908 *Table 3: Bubble mean diameter (D_{mean}) and standard deviation (SD). Experiments performed with*
909 *NAGU at 1- and 3-stage column.*

N (rpm)	$D_{\text{mean}} \pm \text{SD}$ (μm)			$D_{\text{mean}} \pm \text{SD}$ (μm)	
	1-stage column ($\bar{t} = 188$ s)			3-stage column ($\bar{t} = 564$ s)	
	WPC	SCN	TW20	SCN	TW20
200	17 ± 4	50 ± 30	50 ± 40	15 ± 6	20 ± 9
400	17 ± 4	50 ± 20	50 ± 40	13 ± 4	19 ± 7
800	17 ± 4	40 ± 20	40 ± 20	11 ± 3	16 ± 5
1000	15 ± 4	40 ± 20	40 ± 20	11 ± 3	14 ± 7
1200	14 ± 3	30 ± 10	30 ± 20	12 ± 4	13 ± 6

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916 *Table 4: Bubble mean diameter (D_{mean}) and standard deviation (SD). Experiments performed with*
 917 *the RS device, with $\bar{t} = 270$ s and $\bar{t} = 812$ s.*

N (rpm)	$D_{mean} \pm SD$ (μm) $\bar{t} = 270$ s			$D_{mean} \pm SD$ (μm) $\bar{t} = 812$ s	
	WPC	SCN	TW20	SCN	TW20
200	50 ± 20	50 ± 20	90 ± 80	27 ± 8	30 ± 20
400	40 ± 20	21 ± 7	50 ± 20	20 ± 8	30 ± 10
800	40 ± 20	14 ± 5	30 ± 20	16 ± 5	21 ± 9
1000	40 ± 10	14 ± 5	30 ± 20	15 ± 5	22 ± 9
1200	28 ± 7	14 ± 4	20 ± 20	14 ± 5	22 ± 9

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FIGURE 1A

[Click here to access/download;Figure;FIGURE 1A.png](#)

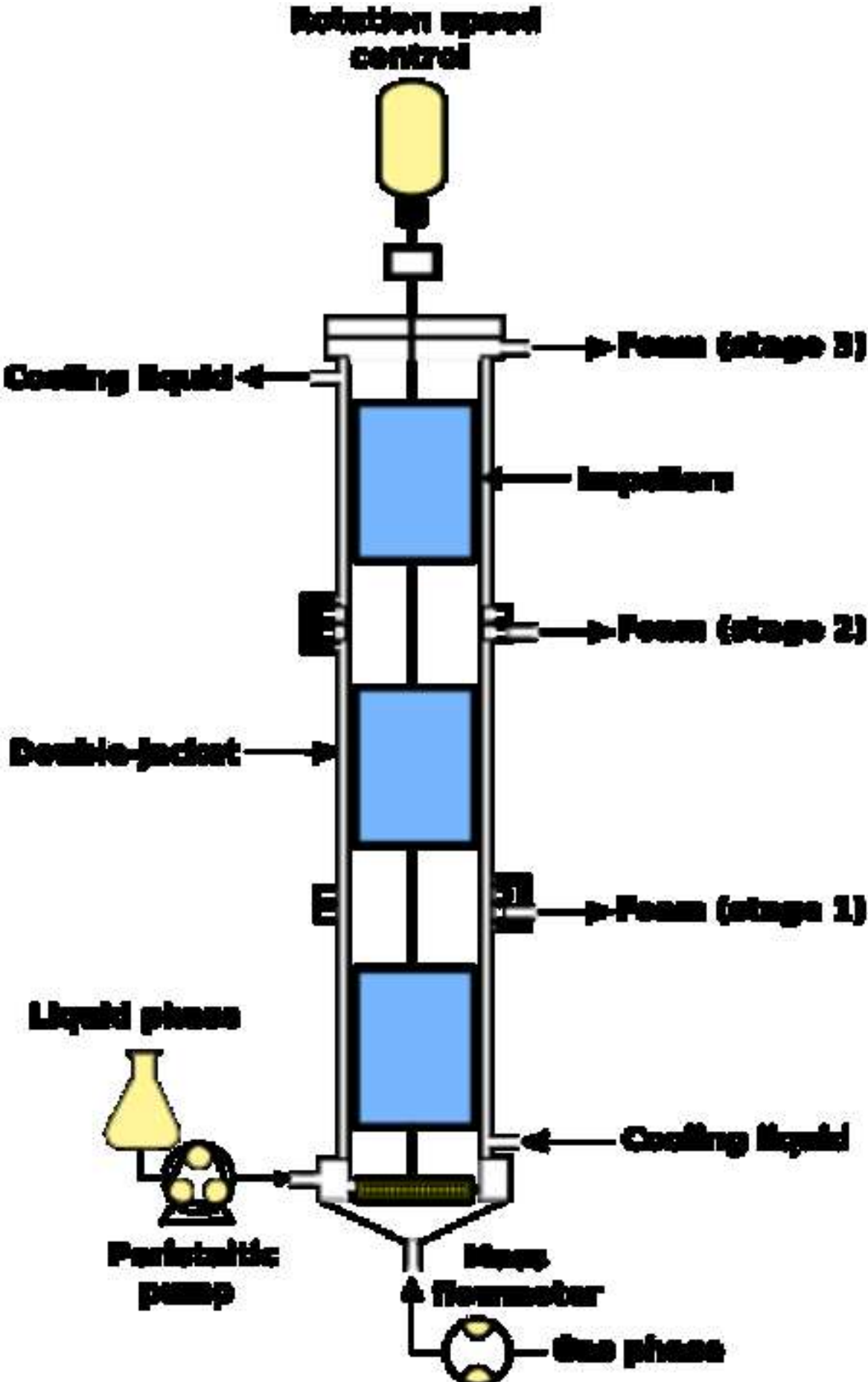


FIGURE 1B

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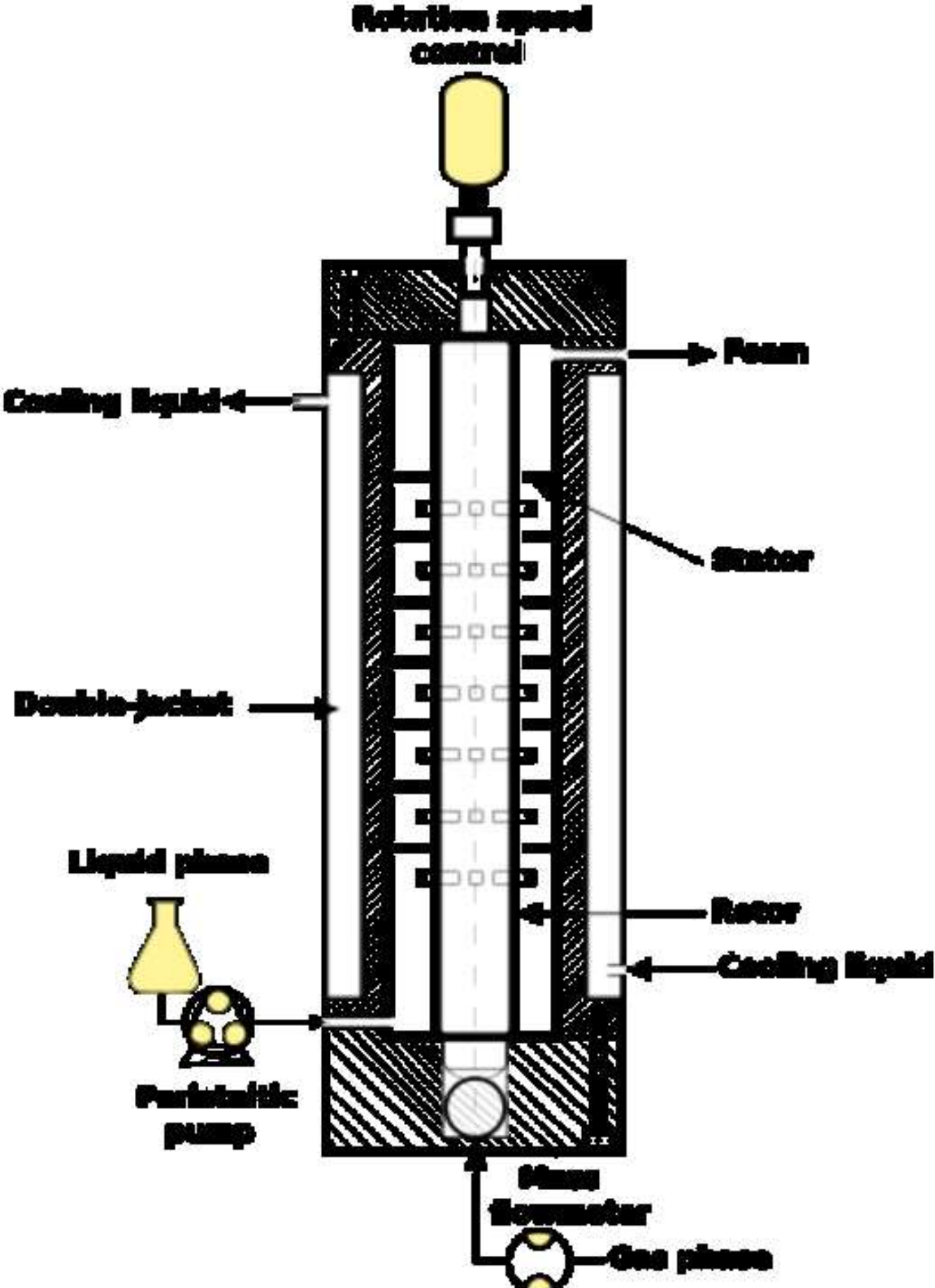
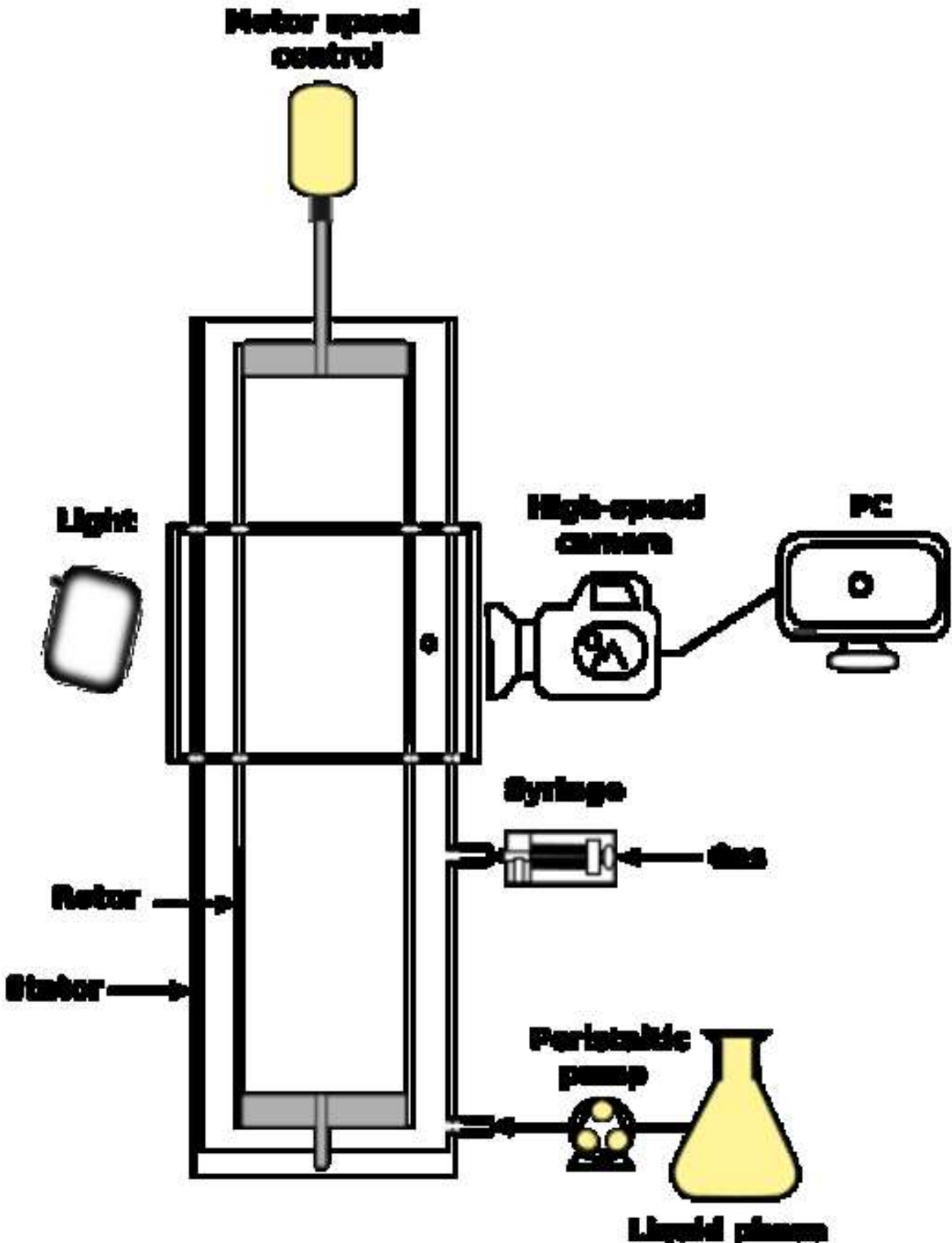


FIGURE 2

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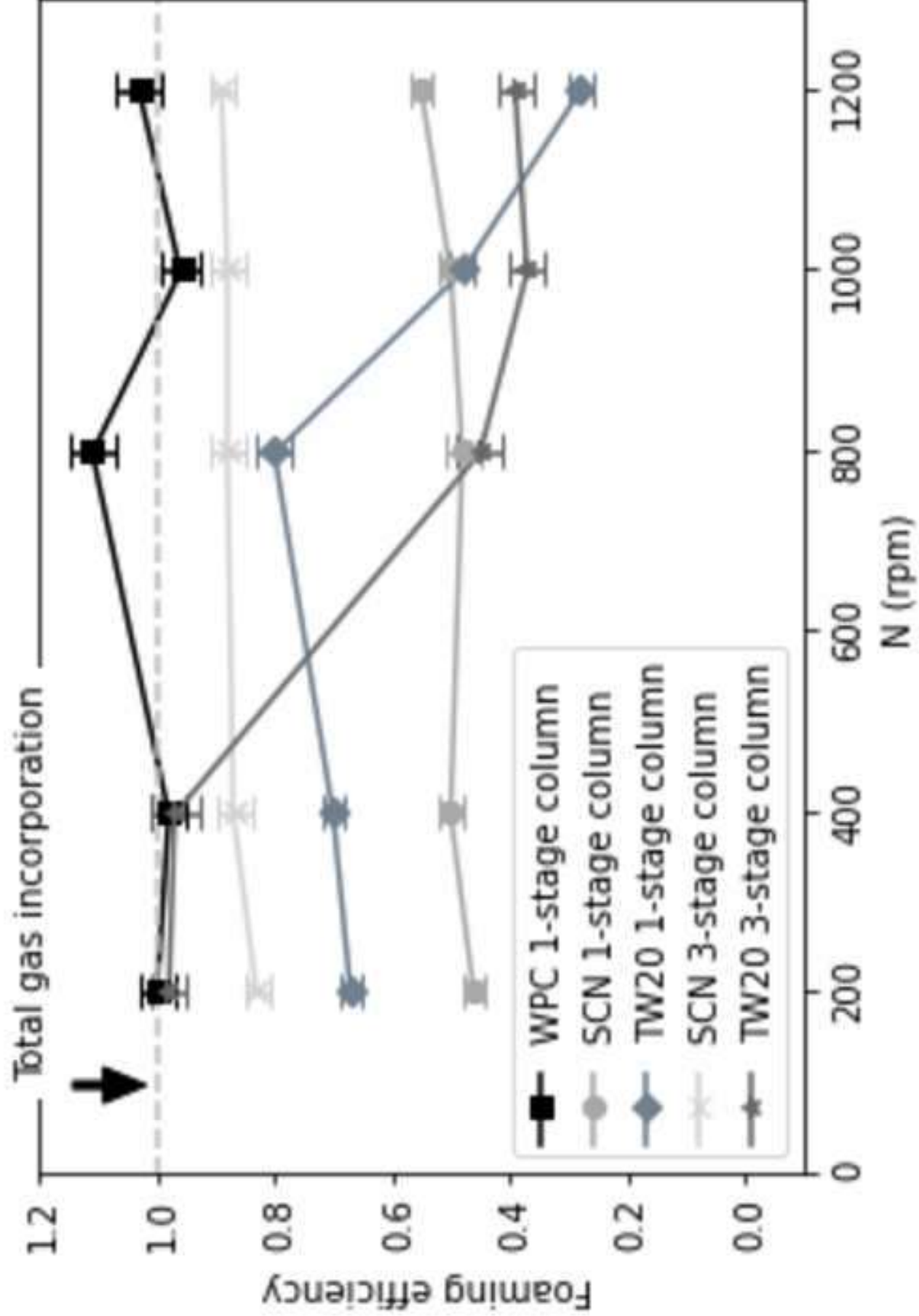


FIGURE 3

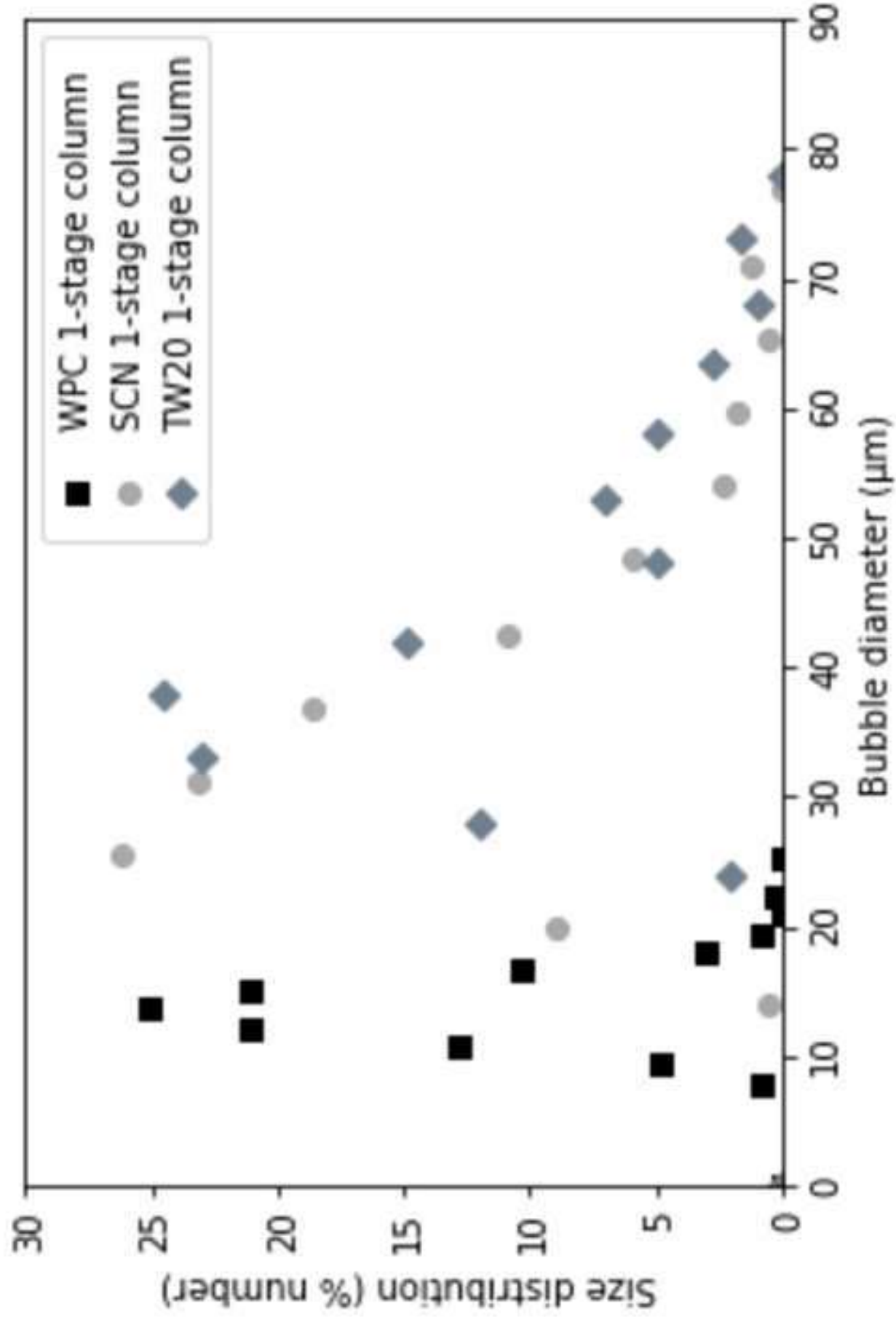


FIGURE 4A

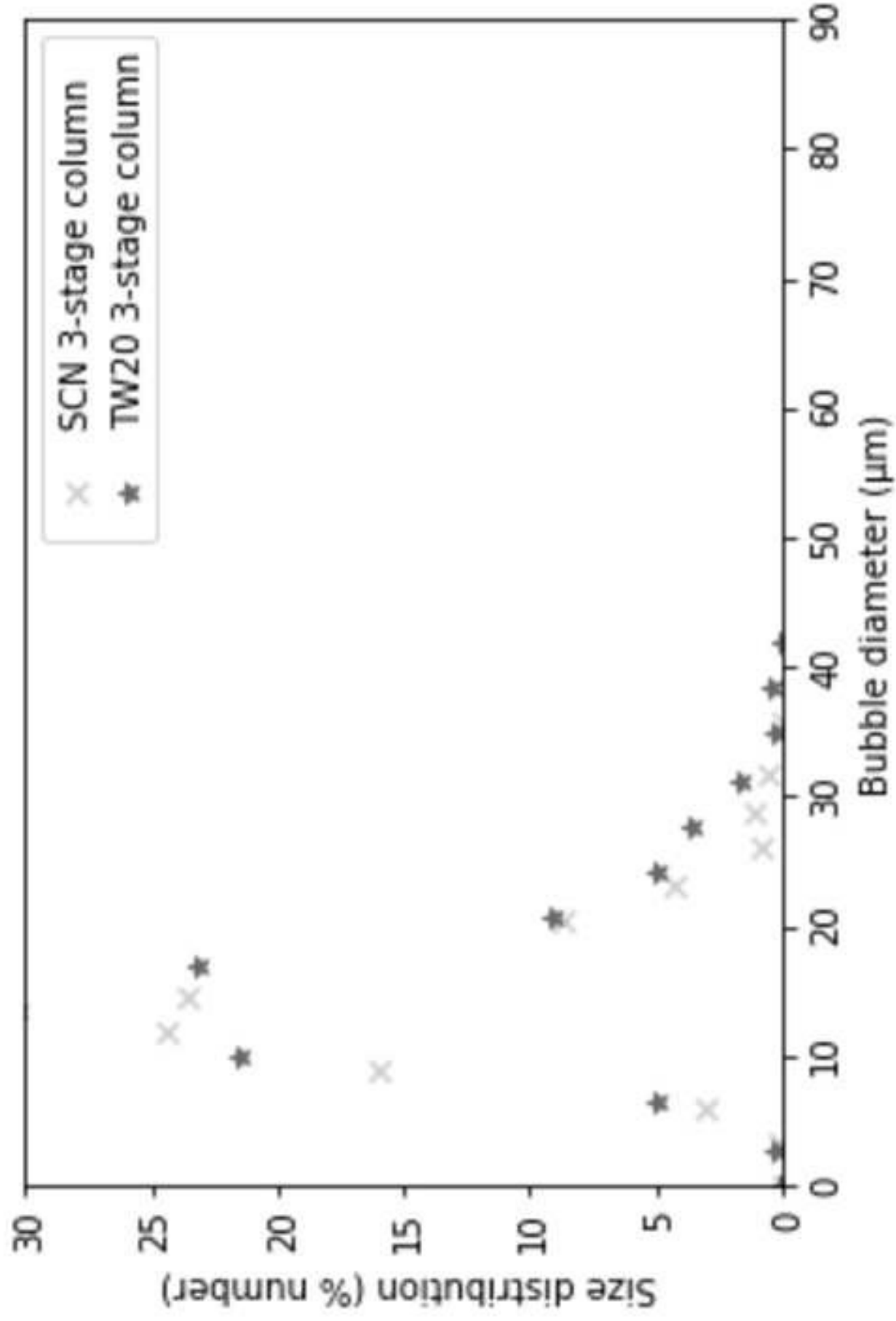


FIGURE 4B

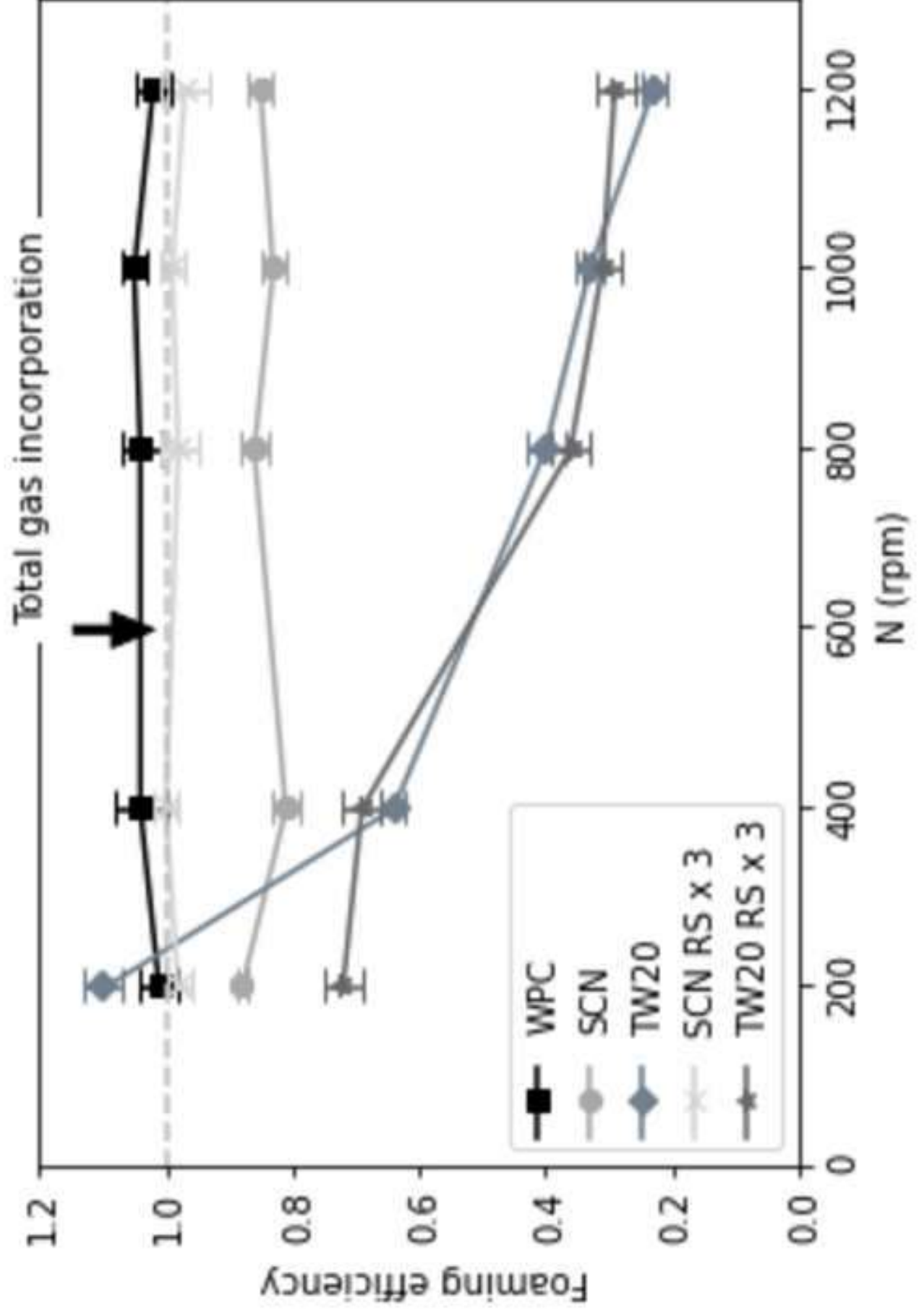
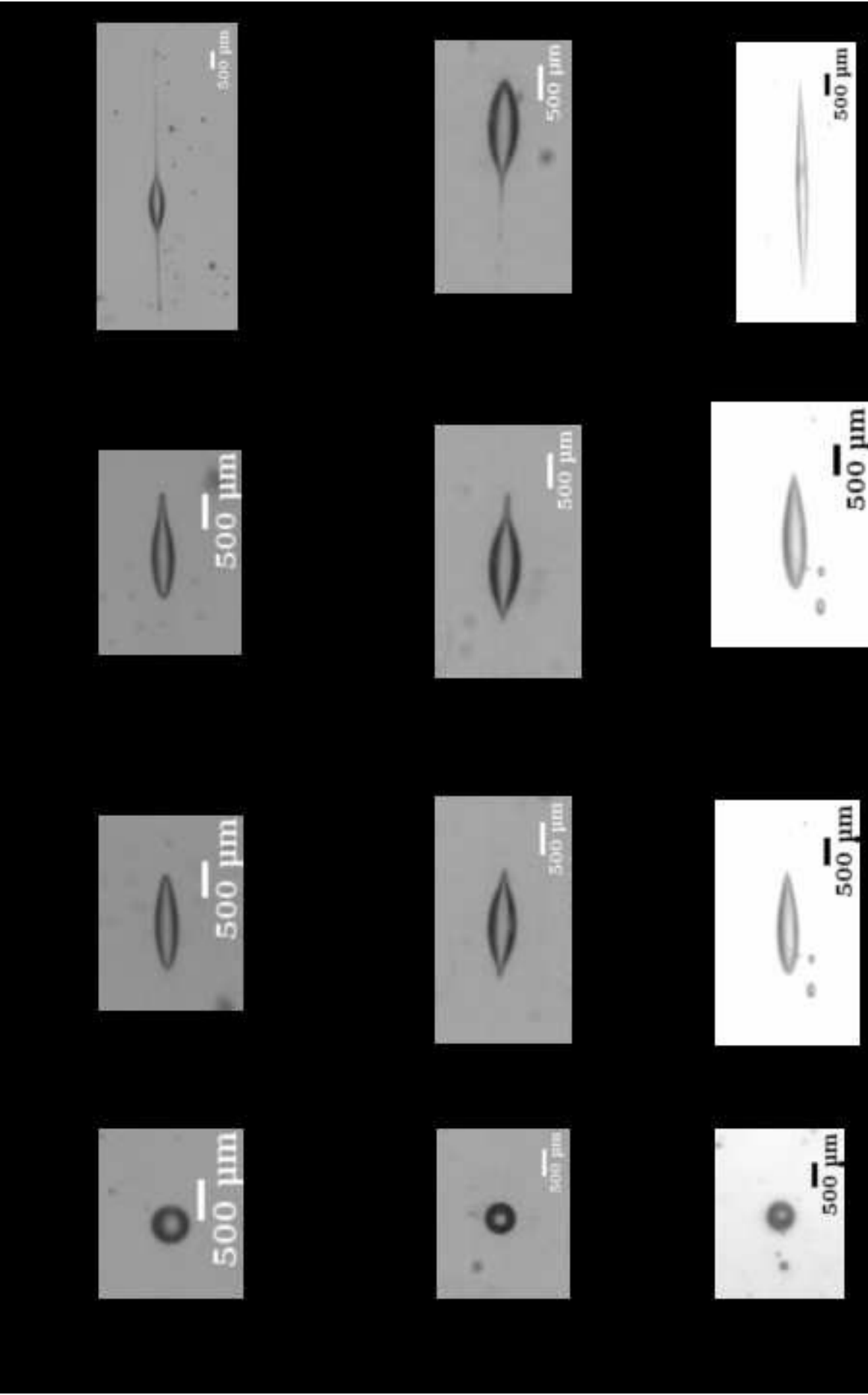
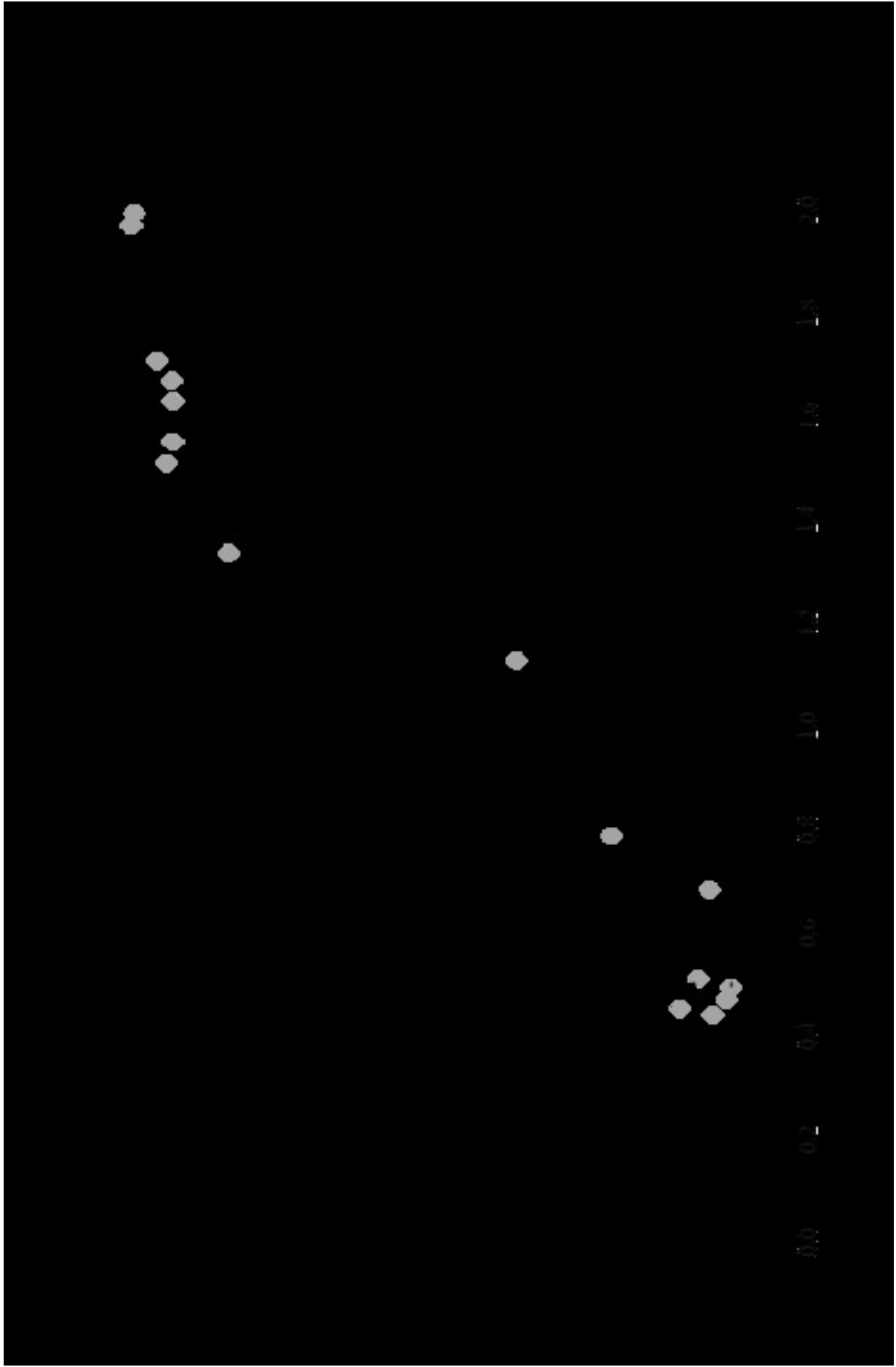


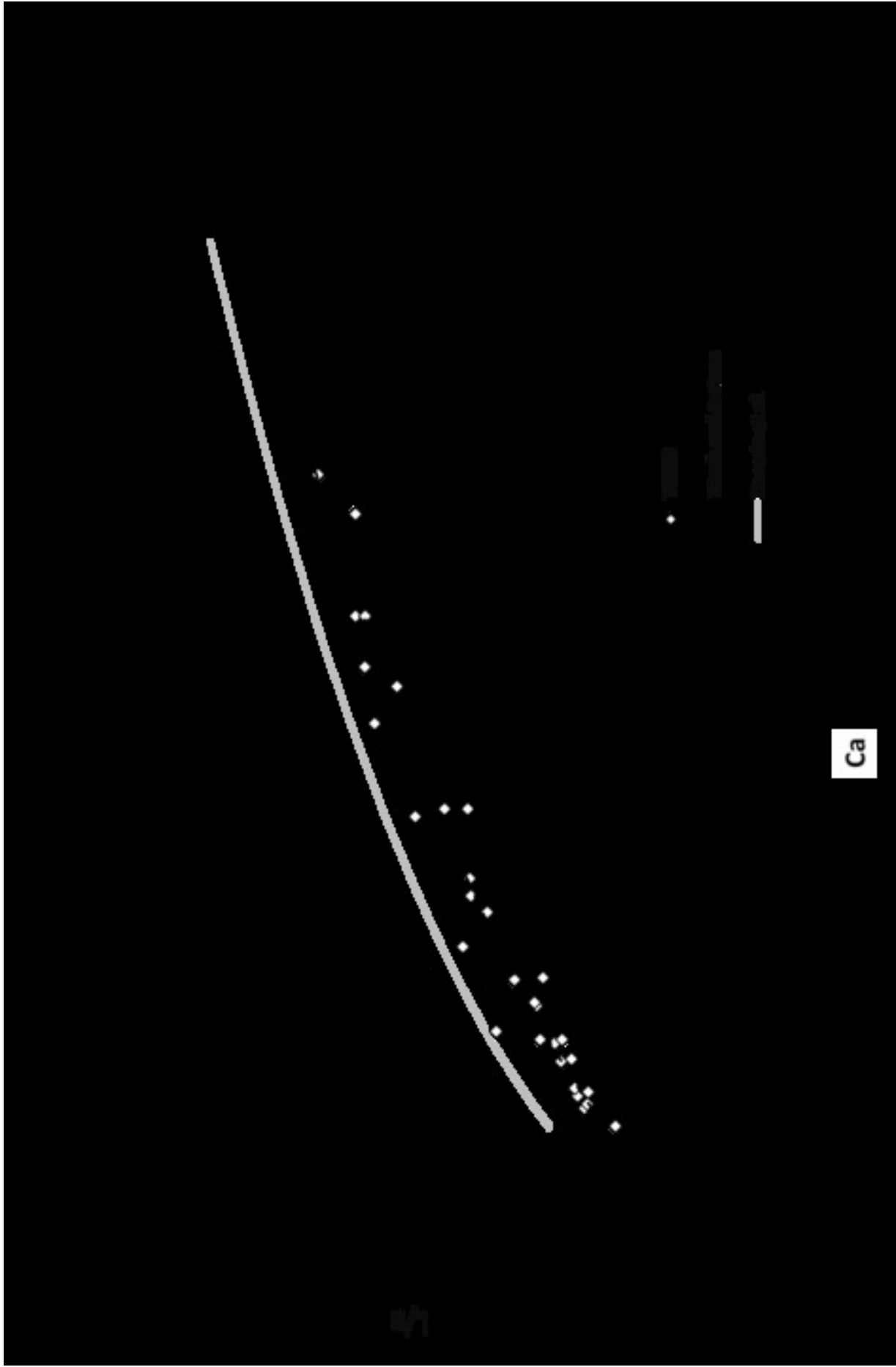
FIGURE 5

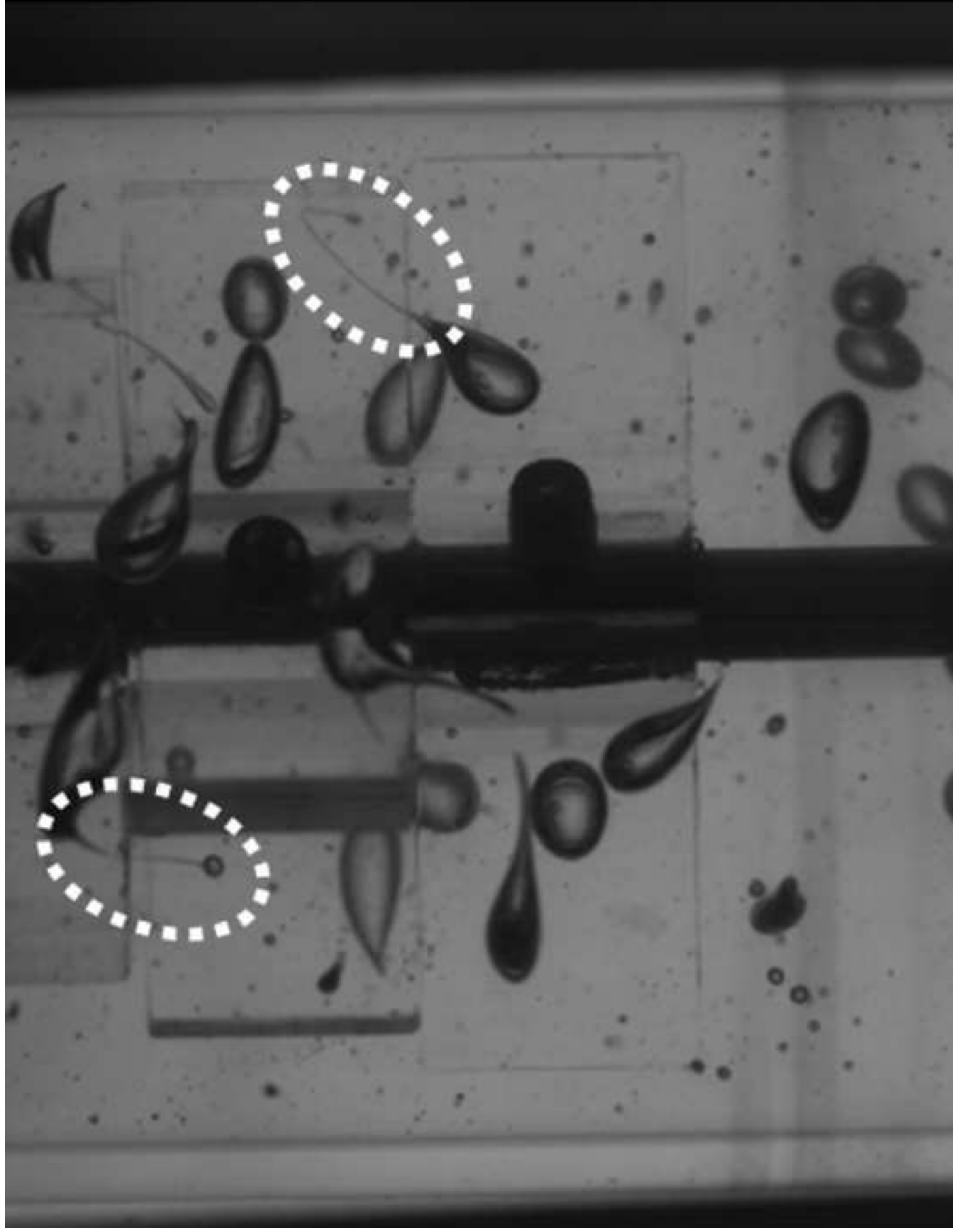
FIGURE 6

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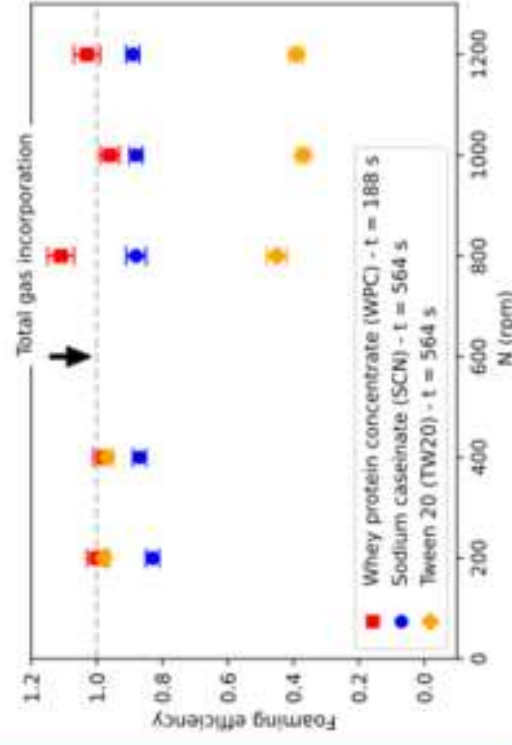




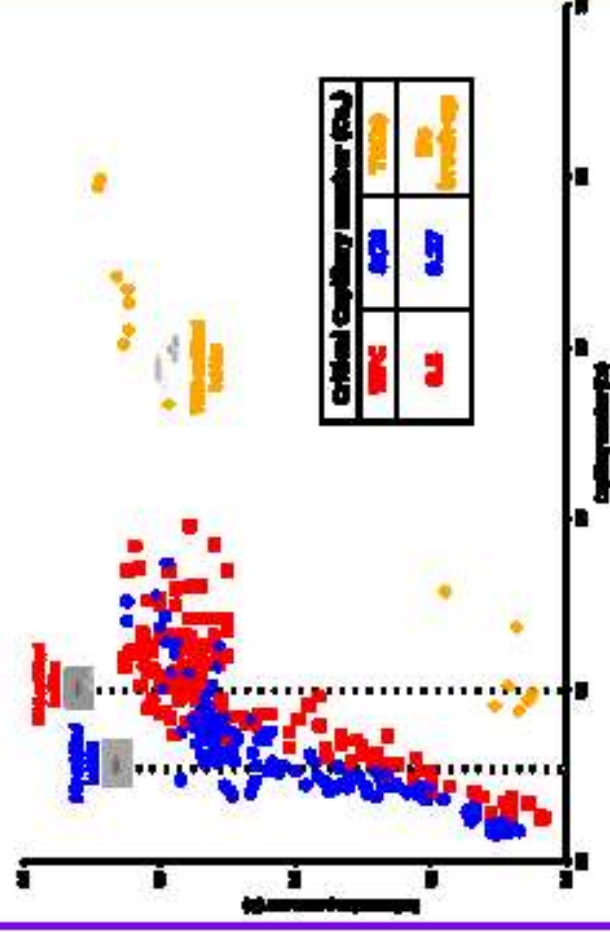




Viscous Newtonian fluid aeration at pilot scale



Single bubble deformation and break-up under simple shear



↘ SCN-stabilized bubbles break at a lower shear rate compared to WPC and yet WPC leads to better pilot-scale foaming efficiency.

↘ The absence of break-up with TW20 could explain the poor foaming results obtained at pilot scale.

1

2 **CRedit authorship contribution statement**

3

4 **Boubakar Sanogo:** Investigation, Formal Analysis, Software, Data analysis, Writing - original draft.

5 **Kaies Souidi:** Investigation, Formal Analysis, Software, Data analysis. **Alain Marcati:**

6 Conceptualization, Methodology, Validation, Supervision, Writing - review & editing. **Christophe**

7 **Vial:** Conceptualization, Methodology, Validation, Supervision, Writing - review & editing.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: