

# *Production of milk foams by steam injection: the effects of steam pressure and nozzle design*

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Jimenez-Junca, C., Sher, A., Gumy, J.-C. and Niranjana, K. (2015) Production of milk foams by steam injection: the effects of steam pressure and nozzle design. *Journal of Food Engineering*, 166. pp. 247-254. ISSN 0260-8774 doi: <https://doi.org/10.1016/j.jfoodeng.2015.05.035> Available at <https://centaur.reading.ac.uk/43510/>

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To link to this article DOI: <http://dx.doi.org/10.1016/j.jfoodeng.2015.05.035>

Publisher: Elsevier

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1 **Production of milk foams by steam injection: the effects of steam pressure**  
2 **and nozzle design**

3

4 Carlos Jimenez-Junca<sup>1\*</sup>, Alexander Sher<sup>2</sup>, Jean-Claude Gumy<sup>3</sup> and K. Niranjana<sup>4</sup>

5 \*Corresponding author: Carlos Jimenez-Junca, e-mail: carlosjj@unisabana.edu.co , tel:  
6 +57 320 845 45 27, Fax: +571 861 55 55

7 <sup>1</sup>Faculty of Engineering, Universidad de la Sabana, Campus Puente el Común, Km.7  
8 Autopista Norte de Bogotá, Chía 25001, Colombia

9 <sup>2</sup>Nestlé R&D Marysville, 809 Collins Ave, Marysville, OH 43040, USA

10 <sup>3</sup>Nestlé PTC Orbe, Rte de Chavornay 3, Orbe, CH-1350, Switzerland

11 <sup>4</sup>Department of Food and Nutritional Sciences, University of Reading, Whiteknights PO  
12 Box 226, Reading RG6 6AP (UK)

13

14 **Abstract**

15 Foam properties depend on the physico-chemical characteristics of the continuous phase,  
16 the method of production and process conditions employed; however the preparation of  
17 barista-style milk foams in coffee shops by injection of steam uses milk as its main  
18 ingredient which limits the control of foam properties by changing the biochemical  
19 characteristics of the continuous phase. Therefore, the control of process conditions and  
20 nozzle design are the only ways available to produce foams with diverse properties. Milk  
21 foams were produced employing different steam pressures (100-280 kPa gauge) and  
22 nozzle designs (ejector, plunging-jet and confined-jet nozzles). The foamability of milk, and  
23 the stability, bubble size and texture of the foams were investigated. Variations in steam

24 pressure and nozzle design changed the hydrodynamic conditions during foam production,  
25 resulting in foams having a range of properties. Steam pressure influenced foam  
26 characteristics, although the net effect depended on the nozzle design used. These results  
27 suggest that, in addition to the physicochemical determinants of milk, the foam properties  
28 can also be controlled by changing the steam pressure and nozzle design.

29 Keywords: cappuccino, milk foams, steam injection, nozzle design, foam properties

## 30 **1. Introduction**

31 Foams are gas-liquid systems, which have applications in different fields: cosmetics,  
32 drugs, oil extraction, chemical industry and food (Herzhaft, 1999). The incorporation of  
33 bubbles into foods helps to improve the texture, appearance and taste whilst decreasing  
34 the caloric content (Campbell and Mougeot, 1999). There are several methods employed  
35 to incorporate bubbles within food structures: mechanical whipping, air injection, chemical  
36 decomposition, fermentation and so on (Campbell and Mougeot, 1999). A less understood  
37 method to generate foams is steam injection, may be because of its exclusive applicability  
38 to froth the milk used in the preparation of coffee based hot beverage such as cappuccino,  
39 latte and mochaccino (Huppertz, 2010).

40 Steam injection frothing is a non-isothermal method, which employs steam flow to draw air  
41 and simultaneously heat up the milk (Silva et al., 2008). Like any foam, the milk foams  
42 produced by steam injection begin to destabilize soon after the steam flow is switched off,  
43 causing their characteristics to change continuously with time. This process is also  
44 accompanied by a drop in temperature which further influences foam properties (Silva et  
45 al., 2008).

46 Foam properties depend on the physico-chemical characteristics of the continuous phase,  
47 the method of production and process conditions (Borcherding et al., 2008; Malysa, 1992).  
48 A great volume of the available information on foaming of food is focused on studying the

49 effect of the surface active agents (surfactants and proteins) on foams properties (Carrera-  
50 Sanchez and Rodriguez-Patino, 2005; Dickinson, 1999; Marinova et al., 2009; Rodríguez  
51 Patino et al., 2008; Wilde et al., 2004). Moreover the published studies on the link between  
52 processing conditions and foam properties are restricted to mechanical agitation based  
53 methods employed for the production of foams (Balerin et al., 2007; Bals and Kulozik,  
54 2003; Indrawati et al., 2008; Thakur et al., 2003).

55 Many designs of coffee machines are commercially available to prepare milk foams, which  
56 employ a variety of steam injector designs (Borgmann, 1990; Giuliano, 1993; Hsu, 2004;  
57 Mahlich and Borgmann, 1989; Stieger and Yoakim, 2006; Stubaus, 1993). Inevitably, each  
58 design produces foam by a different mechanism. The oldest method to produce foam by  
59 steam injection is to use a nozzle that is placed just below the milk surface. The flow of  
60 steam through the nozzle induces air entry. The operator (or barista) moves the milk  
61 container vertically and horizontally at an appropriate frequency to introduce the air and  
62 produce the foam (Giuliano, 1993).

63 Other sparger designs take advantage of a steam ejector principle to restrict the passage  
64 of steam and generate the necessary pressure drop to suck air, or a mix of air and milk, to  
65 generate the foam. The simplest ejector based system consists of a nozzle where the  
66 steam is allowed to expand, thereby generating a very low pressure and drawing the air  
67 through a tube that is connected at the nozzle. The two fluid phases enter a mixing  
68 chamber before being introduced into the milk for generating the foam (Borgmann, 1990).

69 Despite the availability of a large number of patented devices and machines to produce  
70 milk foams by steam injection, there are relatively few studies focusing on the effect of  
71 process conditions on the properties of foams generated (Deeth and Smith, 1983; Goh et  
72 al., 2009; Huppertz, 2010; Kamath et al., 2008; Levy, 2003; Silva et al, 2008). Moreover,  
73 the preparation of barista-style milk foams in coffee shops use homogenized pasteurized

74 semi-skimmed milk, which does not permit the control of foam properties formed by merely  
75 controlling the biochemical characteristics of the milk. The only way to produce foams with  
76 diverse properties, with a given type of milk, is to employ different machine and steam  
77 sparger designs. The aim of this study is to evaluate the relationship between the main  
78 process parameters (steam pressure and nozzle design) and the principal properties of  
79 foams formed.

## 80 2. Materials

### 81 2.1 Milk supply

82 Homogenized pasteurized semi-skimmed milk (brand Freshways) was bought from a local  
83 shop; this was stored in a fridge ( $5 \pm 1^\circ\text{C}$ ) and processed within 3 days of the purchase.  
84 Each batch of milk was characterized by measuring fat, protein, lactose and SNF (solid not  
85 fat) contents using a DairyLab (FOSS, Warrington, UK) and the pH was measured using a  
86 normal potentiometer.

87 Commercial red food colouring (Supercook, Leeds, England) was added to the milk in the  
88 proportion 10 drops/L, in order to enhance the visualization of the liquid/foam interface in  
89 experiments observing the foam generation and stability. The addition of dye at this  
90 concentration does not have effect on milk surface tension or foaming properties (Silva et  
91 al., 2008).

### 92 2.2 Foam generation equipment

93 A steam injection device constructed previously (Silva et al., 2008) which allowed the  
94 formation of foams under controlled and reproducible conditions was used for the  
95 experimental study. A control valve connected to a supply of steam regulated the  
96 pressures between 0 and 280 kPa gauge, and steam was injected at the following specific

97 pressures (100, 180 and 280 kPa) whilst employing three different sparging units  
98 described in the following paragraphs.

### 99 **2.2.1 Confined-jet**

100 This sparger (Figure 1A) is based on a commercial design (Francis X1 espresso machine).  
101 It consists of a plunging-jet nozzle which introduces steam through a 2 mm hole into a  
102 confined cylindrical chamber, 10 mm diameter and 30 mm height, placed 5 mm above the  
103 milk surface. The negative pressure generated in the chamber draws ambient air through  
104 3 holes, 1 mm diameter, located on the cylinder wall, which is dispersed along with the  
105 steam into the milk.

### 106 **2.2.2 Ejector-type nozzle**

107 It was adapted from a commercial espresso machine (Krupps Vivo): Two stainless steel  
108 tubes were connected to a rubber sparger as shown in the Figure 1B, steam was  
109 introduced through one of the tubes, and air was drawn in through the other (7 cm length)  
110 like an ejector system. A mixture of steam and air left the nozzle through a 1mm orifice at  
111 the tip of the rubber unit. The sparging unit was placed in such a way that the orifice on the  
112 rubber unit was located 10 mm below the surface of the milk.

### 113 **2.2.3 Plunging-jet nozzle**

114 A 5 mm commercial nozzle (Figure 1C) with 3 holes of 1 mm each was used. The nozzle  
115 tip was fixed 5 mm above the milk surface, which gave repeatable foam properties.

## 116 **2.3 Foam generation methodology**

117 A fixed volume of milk, 200 mL, was taken in a 1 L graduated cylinder (reading error of  $\pm 10$   
118 mL), and the sparging unit was placed above or below the milk surface depending on the  
119 nozzle studied. The steam was injected at a constant flow rate over a period of time which  
120 gave a maximum temperature of about 70 °C in the milk. The injection time depended of

121 the steam pressure and nozzle type (Table 1). Temperatures were measured continuously  
122 with K type thermocouples connected to a data acquisition system (Grant Systems 10003  
123 Squirrel). One of the thermocouples was placed approximately 2 cm above the anticipated  
124 interface level and the other 2 cm below the interface, in order to to measure the foam and  
125 liquid temperatures, respectively.

## 126 **2.4 Foam properties**

### 127 **2.4.1 Foamability and stability**

128 The foam was allowed to destabilize in the same graduated cylinder where it was formed.  
129 The volume of the dispersion was read continuously from the graduations on the cylinder,  
130 and the cylinder and contents were weighed before and after steam injection, in order to  
131 determine the mass of the steam condensed in the milk. **Total (liquid plus foam) and clear**  
132 **liquid (only liquid) volumes ( $V_T$  and  $V_L$ , respectively)** in the cylinder, and the liquid and  
133 foam temperatures were monitored over time as the foam was left to stand in a controlled  
134 temperature room (18 °C).

135 Foamability was evaluated by obtaining the air volume fraction ( $\phi_0$ ) (Table 2). Although  
136 there are different parameters used to measure the transient stability of foams (Britten and  
137 Lavoie, 1992; Buchanan, 1965; Carrera-Sanchez and Rodriguez-Patino, 2005; Waniska  
138 and Kinsella, 1979), most of the earlier workers have characterized the stability on the  
139 basis of liquid drainage from the foam and the collapse of the foam column. Following the  
140 same vein, the stability of foams was studied by measuring over time: i) the volume  
141 fraction of the liquid drained (LDF) and ii) air release fraction (ARF).

142 The foamability and foam destabilization parameters were determined by undertaking a  
143 mass balance on the basis of the volume measurements made before and after switching  
144 off the steam supply using the equations defined by **Silva et al.**, (2008), (Table 2). When



145 the top of the foam was found to be uneven, an average reading of three points around the  
146 cylinder circumference was taken to represent the mean position of the foam top. The  
147 maximum variation in the readings was 10 mL.

#### 148 **2.4.2 Foam texture**

149 Foam texture was assessed by performing a compression test using a texture analyzer  
150 (TA XT2i, Stable Microsystems, Surrey, UK) at fixed time of 3 minutes of destabilization. A  
151 51 mm diameter cylindrical probe was used in all experiments. The probe compressed the  
152 sample by 5 mm at the test speed of 0.5 mm/s.

153 The equipment was fitted with a 5 kg load cell (sensitivity 0.1 g) for better texture detection  
154 in weaker samples. The maximum force was then selected as the parameter to compare  
155 the texture of different foams.

#### 156 **2.4.3 Bubble size distribution**

157 An optical system with a CCD camera was adapted to measure the bubble size  
158 distribution. The system consisted of a set of TV lenses which allowed visualizing a  
159 minimum size of approximately 10 microns; these lenses were coupled to a CCD camera  
160 which captured the digital images and sent them to a computer to be stored for a further  
161 analysis.

162 The foam was sampled 2 minutes after the steam injection ceased, by using a  
163 polycarbonate spoon designed specially to take the foam directly from the cylinder without  
164 the need to transfer it to another container. The foam was left in the spoon for a minute to  
165 stabilize, prior to taking pictures of 4 different areas in the spoon.

166 The images were edited and processed using the software ImageJ 1.42 and Bubbles Edit  
167 1.1 (a copy licence of BubbleSEdit was given kindly by its author Dr. Xenophon Zabulis

168 from Institute of Computer Science, Foundation for Research and Technology, Crete,  
169 Greece).

### 170 **3. Results and discussion**

#### 171 **3.1 Nozzles characterization**

##### 172 **3.1.1 Steam flow**

173 There were significant effects of the steam pressure ( $p = 0.001$ ) and the type of nozzle  
174 used ( $p = 0.001$ ) on the flow rate of injected steam (Figure 2).

175 Plunging-jet and confined-jet nozzles introduced steam between 1.8 (at 100kPa) and 2.3  
176 (at 280 kPa) times quicker than ejector-type. The flow rate of steam increased linearly with  
177 the pressure, but the rates of increase were different, with the lowest rate being **noted** for  
178 the ejector-type nozzle. The plunging-jet and the confined-jet nozzles can inject steam  
179 almost freely without any flow restriction produced by the air. On the other hand, the  
180 ejector-type nozzle has a mixing chamber where the steam is mixed with the air drawn  
181 (Varga et al., 2009), thus the presence of air in this chamber impedes the steam flow more  
182 **than in other nozzles**.

183 All foams produced were assessed after the milk was warmed between 65 and 70 °C in  
184 order to reproduce the conditions used in the preparation of the traditional barista-style  
185 milk foams in coffee shops.

##### 186 **3.1.2 Performance of nozzles**

187 **When milk foams are produced by steam injection**, the steam is used to warm the milk **as**  
188 **well as** induce the air entry. The final temperature of milk is controlled by the injection time  
189 (at a fixed pressure), and the volume of air introduced depends on the injection time as  
190 well as the mechanism of air entry. The efficiency of any steam-air injecting nozzle can be

191 expressed by the mean value of the ratio of the air and the steam flow rates during  
192 injection.

193 As the air flow depends on the flow of steam, Figure 3 shows a direct variation of the  
194 entrainment ratio with the steam pressure for all nozzles. The rate of change was different  
195 for each nozzle: increasing the pressure, produced slight increase in the entrainment ratio  
196 for ejector-type and confined-jet nozzles which eventually tend towards constant values at  
197 higher pressures. **On the other hand**, the results for plunging-jet nozzle showed a  
198 significant effect of pressure on entrainment ratio with higher rates of changes at higher  
199 pressures.

200 This is a consequence of the mechanism of air entrance: confined-jet and ejector-type  
201 nozzles introduce air by the vacuum caused by steam expansion. As the air and steam are  
202 mixed in a closed space before their injection into milk, an increase in steam pressure  
203 generates greater pressure drop and steam hold-up inside the nozzle, which effectively  
204 reduces the entrainment ratio (Varga et al., 2009). However, the mechanism of air  
205 inclusion is different in the plunging-jet nozzle: the air is introduced as a thin layer  
206 entrained **by** the steam jet **at its** surface. As the steam pressure **rises**, the impact velocity  
207 of the steam jet also increases dragging more air and consequently getting higher  
208 entrainment ratios, as shown by Brattberg and Chanson (1998) and Bagatur et al. (2002).

### 209 **3.2 Bubble size**

210 Two variables were measured to study the bubble populations in foams obtained under the  
211 different conditions of pressure and nozzle type: the Sauter mean diameter ( $D_{32}$ ) which is  
212 related to the bubbles size distribution and the inter-percentile range 10-90 (IPR10-90)  
213 which is a measure of the dispersion in the bubbles size (polydispersity).

214 The effect of pressure on  $D_{32}$  in foams produced with the three nozzles is showed in Figure  
215 4. There was a linear increase in bubble size with steam pressure for each nozzle, but this

216 effect was less marked for plunging-jet nozzle, since the  $D_{32}$  increased by only 3  $\mu\text{m}$  for a  
217 20 kPa increase in pressure. In contrast, the foams produced with confined-jet and ejector-  
218 type nozzles changed bubble size by 11 and 10  $\mu\text{m}$  respectively for 20 kPa increase in  
219 pressure. These inferences can be drawn from the gradient of the best fit lines drawn  
220 through the points shown in Figure 4, for each nozzle. Further, the ejector-type nozzle  
221 produced the biggest bubbles at each steam pressure, while the plunging-jet generated  
222 the smallest bubbles.

223 It is interesting to note that bubble size was affected by pressure more significantly in  
224 foams produced with the confined-jet and ejector-type nozzles than with the plunging jet  
225 nozzle.

226 From the definition of Weber number, which relates the deformation forces acting on  
227 bubbles and the surface tension forces counteracting the bubble deformation, the  
228 maximum stable bubble diameter (Evans et al., 1992) ( $d_m$ ) is given by:

$$229 \quad d_m = \frac{We_c \sigma}{\rho \bar{u}^2}$$

230 where  $\rho$  and  $\sigma$  are the surface tension and liquid density, respectively;  $\bar{u}^2$  is the average of  
231 the squares of the velocity differences in the vicinity of the bubbles; and  $We_c$  is the critical  
232 Weber number at which a bubble splits up, which can be taken as 1.18 - 1.20 for bubble  
233 breakup in a turbulent flow (Evans et al., 1992; Hinze, 1955). Thus, the maximum stable  
234 bubble diameter is inversely proportional to the level of turbulence in the system, which  
235 also depends on the fluid velocity (Evans et al., 1992). Thus, a decrease in the bubble size  
236 is expected with increase in steam pressure on the basis of the existence of  $We_c$ , but this  
237 was not observed, as evident in Figure 4. However, it is necessary to take into account  
238 other processes which occur concurrently or after bubble formation: Varley (1995) found  
239 that bubble size declined with increasing fluid velocity only if the entrainment ratio (ER)

240 remained constant. This was not the case in the present study (Figure 3). Varley (1995)  
241 also suggests that if ER increased with the steam flow, the local gas phase hold up is high  
242 and the probability of bubble collision and coalescence is greater leading to the formation  
243 of larger bubbles. This effect is more pronounced in confined-jet and ejector-type nozzles  
244 compared to plunging-jet, where the mixture of steam and air are confined in smaller  
245 spaces, and the coalescence probability is higher.

246 The other consequence of higher bubble coalescence with increasing ER is a higher  
247 spread in bubbles size (Varley, 1995) as shown in Figure 5. This was more relevant in the  
248 case of confined-jet and ejector-type nozzles than for the plunging jet nozzle. These  
249 results show that the foams became more polydispersed with increasing steam pressure,  
250 and it was more marked in the case of the confined-jet and ejector-type nozzles.

251 Figure 6 presents representative images of the bubbles in foams produced at 280 kPa.

252 The image of bubbles obtained with the plunging-jet nozzle shows smaller bubbles and  
253 more homogeneous bubble size distribution, which allows a better packing of bubbles in  
254 the foam. Further, neither deformation nor compression is observed in the bubbles. The  
255 ejector-type nozzle gave the largest bubbles which appeared deformed and slightly  
256 compressed, whereas the bubbles produced with the confined-jet nozzle were slightly  
257 smaller in size but less packed than those obtained using the ejector-type nozzle.

### 258 3.3. Foamability

259 Foamability is related directly to the quantity of air injected and the capacity of the proteins  
260 to retain this air once the foam is created (Marinova et al., 2009). Since the same type of  
261 milk was used in all experiments, the amount of air incorporation in the foam (Figure 7),  
262 which is also equal to the volume of air injected, depends only on the steam pressure and  
263 nozzle type used to generate the foams.

264 There was a significant effect ( $p < 0.001$ ) of the pressure and nozzle type on  $\phi$  (Figure 7).  
265 The direct relationship of  $\phi$  with the increasing pressure was more evident in the case of  
266 the plunging jet nozzle. No significant changes were observed in foams generated with  
267 ejector-type nozzle. It is important to highlight that  $\phi_0$  was also controlled by the design and  
268 placement of the nozzles: the quantity of air introduced in the case of the confined-jet and  
269 plunging jet nozzles depends on the air entry tube length in the injector-type nozzle (7 cm  
270 in this experiment) and the initial position of the nozzle tip above the milk surface (in this  
271 case, 5 mm). This is because air entrainment ceases when the foam height increases to a  
272 level where it covers the air entry point. This consideration allows explaining the different  
273 effects of pressure change on  $\phi_0$  for each nozzle: as the foam height reaches the position  
274 of the air entrance tube in the ejector-type nozzle, the air flow decreases drastically  
275 regardless of the pressure, resulting in a minimum effect of pressure increase on  $\phi_0$ . On  
276 the other hand, a high speed jet of steam hits the milk surface in the case of the confined-  
277 jet and plunging jet nozzles, creating a cavity in the liquid as consequence of the  
278 stagnation pressure (Ohl et al., 2000). As the speed of the jet increases with the steam  
279 pressure, the cavity size becomes bigger which entraps more air and results in a  
280 significant increasing of  $\phi_0$  with pressure.

### 281 **3.4 Foam stability**

#### 282 **3.4.1 Liquid drainage**

283 Liquid drainage was studied by calculating the liquid drained fraction (LDF) during  
284 destabilization process. Figure 8 shows that foams produced at 100 kPa drained quickly  
285 within the first 2 minutes, whereas those generated at 280 kPa drained more slowly in the  
286 same interval of time. Profiles were more homogeneous after 4 minutes with the exception  
287 of foams produced with the ejector-type nozzle which drained slowly, shedding liquid in  
288 smaller quantities (less than 93%).

289 The influence of pressure was more significant in foams produced with plunging-jet nozzle  
290 in the early stages of destabilization. Thus foams made at 100 kPa drained 92% of liquid  
291 at 2 minutes, whereas foams produced at 280 kPa only drained nearly 80% during the  
292 same time. On the other hand, the steam pressure did not affect the profiles of liquid  
293 drainage in foams generated with ejector-type nozzle, since all foams drained about ~ 78%  
294 after 2 minutes of destabilization for different steam injection pressures.

295 Data on the volumes of liquid drained were fitted to the model developed by Elizalde and  
296 others (1991) to make a quantitative comparison of destabilization and drainage in the  
297 foams (Figure 9). There was a significant effect of the interaction ( $p < 0.019$ ) of the steam  
298 pressure and the nozzle type used on the kinetic parameters. As the initial rate of liquid  
299 drainage ( $R_{OL}$ ) relates to the ability to retain excess liquid in foams with low gas volume  
300 fraction (Britten and Lavoie, 1992), this parameter was used instead of half-life time of  
301 drainage ( $B_L$ ) to compare the rates of drainage. There was a significant effect of the  
302 pressure and nozzle type on rates of liquid drainage ( $p < 0.001$ ): it decreased with  
303 pressure for confined-jet and plunging-jet nozzles, and remained practically constant for  
304 foams produced with the ejector-type nozzle. It is interesting to note the marked effect of  
305 steam pressure on  $R_{OL}$  for foams made with plunging-jet nozzle since it decreased from  
306 2410 to 670 mL/min when the pressure increased from 100 to 280 kPa. On the other hand,  
307 the lowest initial drainage rates were observed in foams produced using ejector-type  
308 nozzle, this is due to the low initial content of liquid in these foams.

309 A variety of factors are associated with the speed and the extent of liquid drainage in  
310 foams: gas flow rate during the foam production, bubble size, initial height of foam column  
311 and liquid properties (Narsimhan, 1991). As these parameters were different and not  
312 controlled in present experiments it is not possible to attribute the observed performance  
313 to any one factor, and a combined effect of these variables is expected. However, a partial

314 explanation can be given by relating the initial rate of liquid drainage with the product of  
315  $D_{32}$  and  $\phi_0$ . Figure 10 shows an inverse relationship:  $R_{OL}$  is higher for smaller products  
316  $D_{32} * \phi_0$  as observed in present study, for example the greatest  $R_{OL}$  was 2488 mL/min which  
317 was observed in foams produced with the plunging jet nozzle at 100 kPa, these had the  
318 smallest bubble size and the highest initial liquid content.

319 If bubbles are greater than the optimum size as stated by Germick and others (1994), the  
320 extent and rate of liquid drainage increases as the bubbles become smaller. This is  
321 because the gradient of plateau border suction (which opposes gravity) is smaller in bigger  
322 bubbles. On the other hand, a high initial content of liquid in the foam generates more  
323 homogeneous foams; the gradient of plateau border suction is smaller and the gravity  
324 accelerates drainage.

#### 325 **3.4.2 Air release**

326 **As** a consequence of liquid drainage, the liquid film between bubbles becomes thinner and  
327 eventually ruptures. This phenomenon plus the disproportionation process result in foam  
328 collapse (Carrier and Colin, 2003), which is accompanied by air release. Figure 11 shows  
329 how the air release fraction (ARF) for the different foams changes with destabilization time.

330 The value of this fraction after 10 min depended on the steam pressure employed and the  
331 nozzle used to create the foam. When the ejector-type nozzle was used, ARF only  
332 increased for steam pressures between 100 kPa and 180 kPa, remaining unaltered at 280  
333 kPa. In the case of the plunging-jet nozzle, the ARF increased for the same three pressure  
334 values. When the confined-jet nozzle was used, the ARF remained unaltered for all three  
335 steam pressure values. Figure 11 also shows the rate of air release was higher in the case  
336 of confined-jet and ejector-type nozzles during the first 5 minutes, when the steam  
337 pressure employed was 100 kPa; thereafter, the profiles were similar for these two  
338 nozzles, with the ejector-type nozzle giving slightly higher values.



339 Even though Britten and Lavoie (1992) found three distinct zones of rates for gas release  
340 from milk protein foams, Figure 11 only shows a roughly constant rate of foam collapse  
341 which corresponds to the second stage of the rate profiles observed by Halling (1981).  
342 These differences may be attributed to the different foaming temperatures: Britten and  
343 Lavoie (1992) worked at 20 °C, so the collapse of the foam column was slower, and all  
344 three stages were observed. On the other hand, the temperature of the present foams was  
345 65 °C at the beginning of destabilization, so the foam collapse was rapid and the time  
346 necessary to achieve the critical lamella thickness was likely to be so short that the first  
347 stage is not noticeable. Moreover, the final stage was also not observed in this study  
348 because it generally occurred after very long times, for instance, Britten and Lavoie (1992)  
349 observed this stage after 40 min of destabilization.

### 350 **3.5 Foam texture**

351 Figure 12 presents the compression force at a strain of 5% for foams produced with the  
352 different combinations of steam pressure and nozzle design.

353 There was a significant effect of steam pressure ( $p < 0.001$ ) on compression force, which  
354 increased with the pressure in all foams, but the change was greater in foams made with  
355 plunging-jet nozzle, which also produced the strongest foams at each pressure. Although  
356 there is no information available which can explain the differences between compression  
357 force values, the differences can be related to the bubble size, extent of polydispersity and  
358 gas volume fraction. Figure 13 shows the changes in compression force with specific  
359 interfacial area in the different foams. There is a decrease in the force with the interfacial  
360 area, which means that the foams are easier to compress when the bubble size is small  
361 and/or the holdup is high. The fact that there is a curve for each nozzle suggests there are  
362 other factors intrinsic to each steam nozzle influencing the compression forces.

## 363 **4. Conclusions**

364 The use of different type of nozzles and steam injection pressures produce foams with  
365 significantly different properties. The increase in steam pressure reduced the steam  
366 injection time required to produce the foams and improved foamability, stability and texture  
367 in the foams.

368 The mechanism of air entry determined the extent of changes in foams properties when  
369 steam pressure increased. Thus, in nozzles where the mixture of steam and air was  
370 confined (confined-jet and ejector-type nozzles), increasing steam pressure strongly  
371 influenced foam bubble size and texture, whereas the change in these properties was less  
372 marked when the air was introduced unconfined as in the case of the plunging-jet.

373 In general, foams produced between steam pressures of 180 and 280 kPa with the  
374 plunging-jet nozzle had desired combination of low bubble size, high foam stability and  
375 stiffness (measured as a compression force).

376 Finally, it was found that gas volume fraction and bubble size are related to liquid drainage  
377 and compression force, since the initial rate of liquid drainage changed inversely with the  
378 product of  $\phi_0$  and  $D_{32}$ , and the compression force decreased with the specific interfacial  
379 area which is proportional to  $\phi_0/D_{32}$ .

## 380 **5. Acknowledgements**

381 Dr. Xenophon Zabulis from the Inst. of Computer Science, Foundation for Research and  
382 Technology (Greece), is acknowledged for providing a copy of the software Bubbles Edit  
383 1.1 to analyze the bubble size. The financial support of Nestle and the Engineering and  
384 Physical Sciences Research Council (EPSRC), U.K., is also gratefully acknowledged.

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