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Effect of milk homogenisation and foaming temperature on properties and microstructure of foams from pasteurised whole milk

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Dedicated to Wolfgang Buchheim on the occasion of his 70th birthday.

Abstract

Differently homogenised and HTST-heated milk (3.5% fat) was foamed at temperatures between 4 and 60 °C. Foaming was achieved by air injection through fritted glass. Initial foam density, drainage and corresponding bubble size were analysed. Transmission electron microscopic (TEM) images completed the study. The studies showed that whole milk was better foamable between 50 and 60 °C than at lower temperatures. This was mainly due to the completely liquid milk fat and the increased protein adsorption at the air–serum interface. The resulting bubbles of these two foams maintained their spherical shape also for 20 min of draining. However, the average bubble diameter and the drainage mass in relation to the initial foam mass increased from about 20 g/100 g after 1 min to about 80 g/100 g after 20 min. It was surprising to learn that milk homogenisation and corresponding fat globule size had only marginal effect on foam formation and stability. TEM images suggested that the air–serum interface consisted mainly of protein monomers and oligomers, while casein micelles were not directly adsorbed. The membrane of the homogenised fat globules was destroyed near the interface and coalesced liquid fat formed a restricted film on the bubble that was obviously of minor importance for the foam properties.

Keywords: Whole milk; Homogenisation; Foaming temperature; Bubble size; Foam microstructure

1. Introduction

A diverse range of foods are aerated using a similarly varied assortment of processing methods. However, not all is known about aerated systems which consist of many different types of molecules (Campbell & Mougeot, 1999; Dickinson, 1992; Leser & Michel, 1999). This is also valid for the varied applications of milk foams which became more and more utilized, in particular as topping on popular coffee beverages such as cappuccino. The foaming properties of milk have been studied since the beginning of the last century, but the aim of this early work was to decrease foam formation during milk processing (Rahn, 1922; Siedel & Hesse, 1900). Although this problem still exists, most of the papers published during the last three decades have dealt with foams of isolated milk proteins (Clarkson, Cui, & Darton, 1999a, 1999b; Damodaran, 2005; Damodaran & Paraf, 1997; Dickinson, 2003; Graham & Phillips, 1976; German & Phillips, 1994; Halling, 1981; Kinsella & Phillips, 1989; Walstra & de Roos, 1993), and with fat-stabilized whipping cream (Besner & Kessler, 1998; Brooker, 1990; Brooker, Anderson, & Andrews, 1986; Buchheim, 1991; Smith, Goff, & Kakuda, 2000; Stanley, Goff, & Smith, 1996), or ice cream (Berger, 1997; Buchheim, 1998; Goff, 1997, 2003).

Only a few authors have studied the complex interactions of the different milk proteins and the resulting properties of milk foams. Ward, Goddard, Augustin, and McKinnon (1997)

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reported that the addition of Ca chelating agents to milk increased foam volume but had no clear effect on foam stability. Addition of Ca to skim milk depressed foam formation. Obviously, the increase in serum protein (non-micellar protein) on addition of EDTA to milk contributed to improved foaming properties by increasing the availability of the proteins for formation of the primary air–serum interface.

The first electron microscopic images of the bubble surface in milk led to the assumption that it consists of a two-dimensional network of casein micelles (Mulder & Walstra, 1974). Brooker (1985) showed that the attachment of casein micelles to the interfacial layer was reversible. β-Lactoglobulin, α-lactalbumin and β-casein seem to be the main constituents of the interface (Brooker, Anderson, & Andrews, 1986). The stability of these protein-stabilized foams may be influenced by adsorption of other milk constituents, in particular emulsified milk fat (Brooker, 1993).

Foaming of fat-containing milk was mainly carried out at temperatures where both crystallised and liquid fractions were present within the fat globules that favoured partial coalescence by mechanical input. Anderson and Brooker (1988) found that in the range of 5–15 °C the ease of foam formation (foaming rate) decreased as fat content (0–1.5%) and temperature increased. However, changing the temperature from 5 to 15 °C had little effect on the collapse rate in spite of the large change in liquid fat content. Prins (1986) claimed that spreading of liquid fat at the interface and local thinning of the protein film followed adsorption resulting in less stable lamellae and collapsing bubbles. The effect of a foaming temperature above 20 or 37 °C, where the milk fat is predominantly or completely molten, has been analysed rarely until now. That is also valid for the effect of milk homogenisation. Hoffmann, Wieczorek, and Borcherding (2002) foamed differently processed samples of the same batch of raw milk with customary devices at 50 and 70 °C. They showed that homogenised milk fat (max. 3.5%) reduced the attainable foam volume, but had no negative effect on the foam stability. Unfortunately, the various published foaming results are hardly comparable because different foaming devices and conditions were used in each instance.

The objective of the present work was to investigate the effect of milk homogenisation and foaming temperature on properties and microstructure of foams prepared from pasteurised whole milk. The studies on hand focused mainly on the influence of fat globules on whole milk foams. The foaming properties of the milk proteins were not considered in detail. Foaming was achieved by air injection through fritted glass without additional mechanical treatment.

2. Materials and methods

2.1. Preparation of whole milk samples

Raw milk was obtained from the experimental farm of the Federal Research Centre for Nutrition and Food, Kiel. After skimming in a separator (Westfalia, Oelde, Germany) at 45 °C, the milk was adjusted to 3.5% fat by mixing skim milk and cream. This whole milk was homogenised at 50 °C using different pressure conditions (unless otherwise stated 200/50 bar in a two-stage device of APV, Unna, Germany) and subsequently pasteurised (high-temperature short-time (HTST-) heated at 73 °C for 20 s using a plate heat exchanger of APV, Unna, Germany). All batches were filled into autoclaved glass bottles (1 l) with screw caps and stored at 5 °C.

2.2. Characterisation of milk samples

2.2.1. Apparent viscosity and surface tension

Apparent viscosity of the milk samples was determined at 50 °C using a rheometer (UDS 200, Physica Messtechnik, Stuttgart, Germany), equipped with a cone and plate geometry. After a pre-shear (20 s) and an equilibration time (60 s), a flow curve with increasing and decreasing shear rate (50 to 1000 s^{-1}, 20 measurement points, each for 5 s) was recorded. The viscosity was calculated on the basis of the data points in the linear area (800–1000 s^{-1}) and determined in duplicate.

Double surface tension measurements were performed at 4–20 °C after an equilibration period of 20 min using the Pendant Drop Method (Drop Shape Analysis System 10 Mk2, and software DSA 1, Krüss, Hamburg, Germany). The surface tension (σ) between 30 and 60 °C could only be calculated according to a formula of Houška et al. (1994):

$$\sigma = 4.74 * 10^{-2} - 9.02 * 10^{-5} t - 3.79 * 10^{-7} t^2$$

The formula is based on empirical data (0–80 °C) from four different experimental studies. It considers thermal changes such as denaturation of whey proteins. The calculated surface tension data above 20 °C were used as a qualitative impression only.

2.2.2. Measurement of the particle size distribution

The particle size distribution in whole milk was analysed by a laser diffraction spectrophotometer (Coulter LS 230, Beckman Coulter, Krefeld, Germany). The fat globule diameter was calculated with the refraction indices of Hinrichs (1994).

2.3. Foaming apparatus

The foaming apparatus (Fig. 1) was a further development of the equipment described by Fains, Bertrand, Baniel, and Popineau (1997), Ralet and Gueguen (2001), Waniska and Kinsella (1979), and Yu and Damodaran (1991). It consisted of a double-walled glass body that allowed control to a chosen temperature. The milk was foamed by constant injection of compressed air (4 l/h) through a porous glass frit (pore diameter 9–15 μm) at the bottom of the glass body. The foam developed in a volumetric glass flask positioned above. After foam formation of 200 cm^3, the foam-filled flask was closed with a stopper, removed from the double-walled glass body and taken to a funnel with a glass membrane (pore diameter 90–150 μm) for determination of characteristic foam properties. Each foaming experiment was carried out in triplicate.

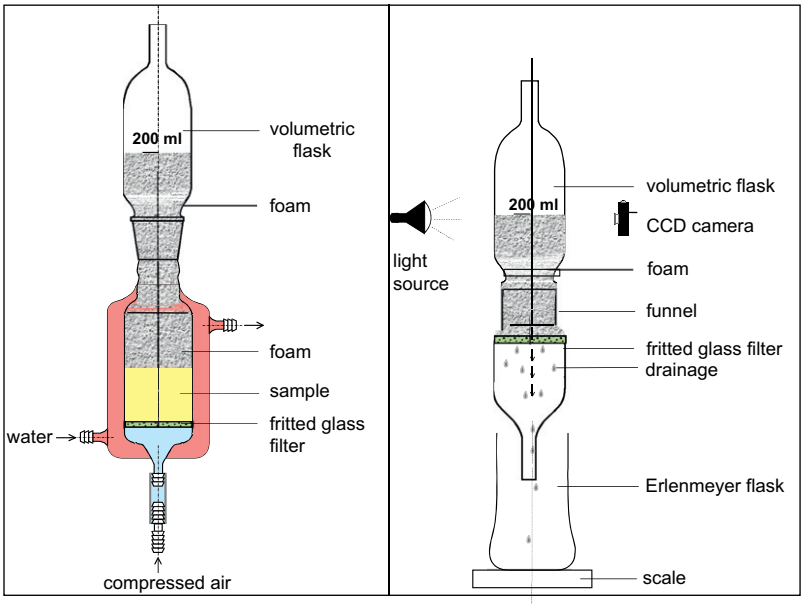

Fig. 1. Configuration and operating mode of the foaming apparatus.

2.4. Characterisation of milk foam properties

2.4.1. Foam density and drainage

The foam density was determined immediately ($t = 0$ min) after formation of 200 cm^3 foam by weighing the filled (and empty) flask and was calculated according to the formula:

$$\text{density}_{\text{foam}}\left[\text{g/cm}^3\right] = \frac{\text{mass}_{\text{foam}}[\text{g}]}{\text{volume}_{\text{foam}}[\text{cm}^3]}$$

Determinations were performed in triplicate. The coefficient of variation in the studies on hand was less than 5%.

For drainage measurements, the foam-filled (200 cm^3) glass flask was carefully put on a funnel with a glass membrane that was located above another flask on a pair of scales. The amount of drainage having dropped into this flask was recorded and related to the initial foam mass (g/100 g). Determinations were performed in triplicate.

2.4.2. Image analysis of foam bubble size distribution

Image analysis enabled a detailed view of the foam structure and an analysis of the time-dependent bubble size distribution. All pictures were captured with a digital microscope camera (DMC 1, Polaroid Corp., Cambridge, MA, USA) including a macro zoom lens (10×, $f = 20$–200 mm, F 5.6, EHD Imaging, Damme, Germany). Images were digitised with the software Image-Pro Plus Version 4.1 (Media Cybernetics, Silver Spring, MD, USA). The photos of the foam bubbles were taken after 1 and 20 min. The segmentation of the image occurred with the threshold function, and a watershed transformation enabled the separation of touched bubbles. Only complete bubbles were analysed. The diameter (d) was calculated from at least 200 bubbles of each foam sample. For evaluating the bubble size distribution, the data were divided into classes from 0.0 to 1.0 mm (class order (x) = 0.1 mm) and the percentages as well as their standard deviation within the classes were calculated on the basis of triplicate experiments.

2.4.3. Electron microscopy

A transmission electron microscope (TEM, Tecnai 10, FEI Company, Eindhoven, Netherlands) was used for the analysis of the internal structures of milk foams. Jet-freezing (Cryo-jet JFD 30, Bal-Tec, Liechtenstein) was chosen for the preparation of the foams. About 1 µl of foam was placed on a grid (gold, 7 µm thick, 400 mesh, Bal-Tec No. LZ 01859 KN) placed between two specimen carriers (copper, Bal-Tec No. LZ 02131 VN and LZ 02132 VN). One of them had a small cavity to prevent destruction of the foam. This sandwich was immediately frozen in the apparatus by a jet of liquid propane. The frozen samples were stored in liquid nitrogen. In the next step, the samples were fractured using the device for cryo-jet sandwiches and replicated in a Balzers BA 360M (Balzers, Liechtenstein). The replica were examined in the TEM at 80 kV (Schrader, Buchheim, & Morr, 1997).

3. Results and discussion

3.1. Influence of the foaming temperatures (4–60 °C)

Formation and stability of the whole milk foams depended strongly on the foaming temperature. Foams prepared at a milk temperature between 4 and 30 °C were largely unstable; their air bubbles collapsed within a few minutes. Foaming at 20 °C led to a completely inadequate formation of bubbles and no foam analysis was feasible. Surprisingly, the foam prepared at 10 °C had the highest initial density of about 0.19 g/cm^3 (Table 1). The density of the foams produced at 40–60 °C was slightly smaller (0.17–0.18 g/cm^3). Digital images (Fig. 2) showed that the foam made at 30 °C consisted of large

Table 1
Effect of foaming temperature on selected properties of liquid and foamed homogenised and HTST-heated whole milk

Foaming temperature (°C)	Apparent viscosity[a] (mPa s)	pH value	Surface tension[b] (mN/m)	Foam density (g/cm^3)	Number average diameter of foam bubbles d_{10} (mm)		Drainage/initial foam (g/100 g)	
					After 1 min	After 20 min	After 1 min	After 20 min
4	3.9	6.75	47.0	0.130 ± 0.013	n.d.	n.d.	53 ± 11	95 ± 1
10	4.0	6.67	46.5	0.188 ± 0.002	n.d.	n.d.	34 ± 5	92 ± 6
20	2.3	6.64	45.4	no foam	no foam	no foam	no foam	no foam
30	1.9	6.57	44.4	0.149 ± 0.002	n.d.	n.d.	48 ± 2	96 ± 2
40	1.5	6.52	43.2	0.172 ± 0.006	0.233 ± 0.006	n.d.	11 ± 1	83 ± 1
50	1.3	6.46	41.9	0.170 ± 0.001	0.183 ± 0.001	0.300 ± 0.020	21 ± 1	77 ± 1
60	n.d.	6.40	40.6	0.177 ± 0.002	0.135 ± 0.011	0.258 ± 0.011	24 ± 1	80 ± 1

n.d., not detected: quantity of foam bubbles was to low for statistical evaluation (see Fig. 2).
[a] Measurements were carried out in duplicate. Reproducible determination of milk viscosity was not feasible at 60 °C.
[b] Above 20 °C, the window of the measuring chamber misted up. Therefore, the surface tension between 30–60 °C was calculated according to a formula of Houška et al. (1994).

angular bubbles after 1 min drainage. These bubbles had a diameter of 1–3 mm and the corresponding lamellae of about 0.16 mm. A rise in temperature from 40 up to 60 °C resulted in a smaller average diameter and a narrower bubble size distribution of the spherical bubbles. The d_{10} value decreased from 0.23 to 0.14 μm (Table 1). Foams made at 50 or 60 °C contained more than 50% air bubbles with a diameter between 0.1 and 0.2 μm (Fig. 3). Drainage of these two foams increased from about 20 g/100 g after 1 min to about 80 g/100 g after 20 min (Table 1). This corresponded with a distinctly larger average bubble diameter greater than 0.25 μm. Foaming at 40 °C resulted in a drainage of more than 80 g/100 g after 20 min. This foam had a strongly altered appearance and finally consisted of large polyangular bubbles (diameter 1–5 mm) and smaller bubbles within the lamellae (Fig. 2).

The homogenised and HTST-heated whole milk samples contained small fat globules coated by milk proteins which adjusted their hydrophilic groups to the milk serum. At 20 °C, fat globules consisted of about 20% of crystallised and about 80% liquid fat which was obviously detrimental to the foam formation. Above 37 °C, milk fat existed solely in a liquid state and the fat globules were more resistant against mechanical treatment.

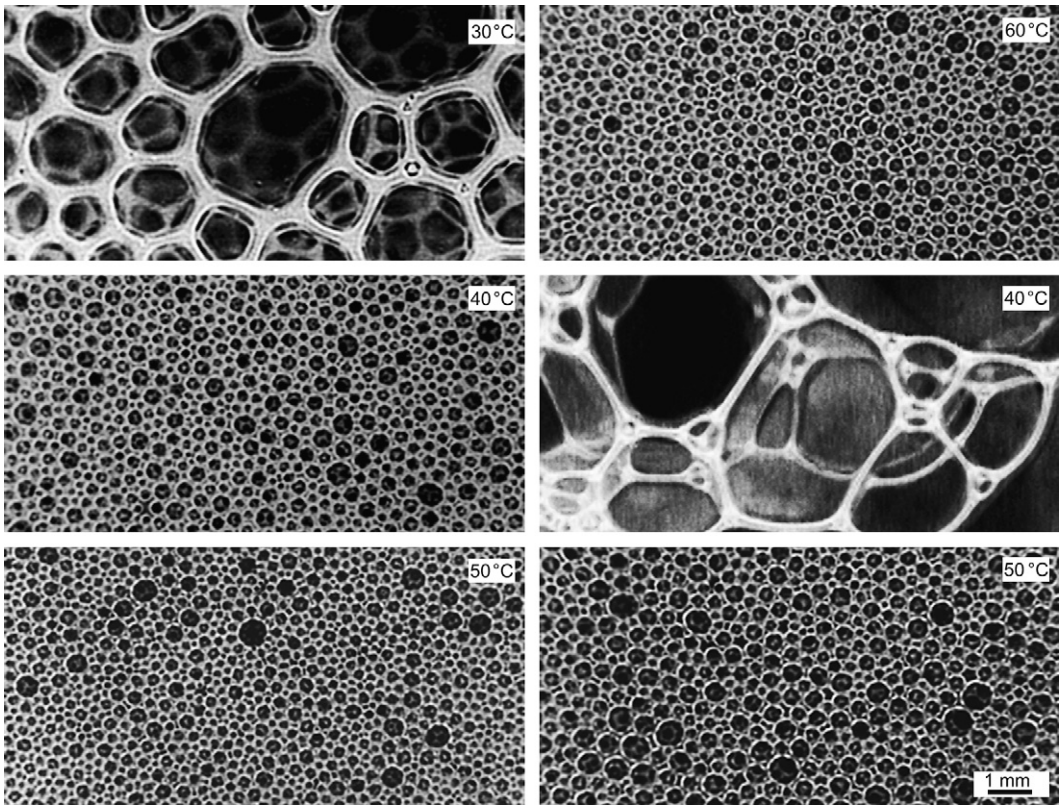

Fig. 2. Digital images of foams from homogenised and HTST-heated whole milk in relation to the foaming temperature after 1 min (left) and 20 min (right) of drainage; 30 °C/20 min: no foam; 60 °C/1 min: no image.

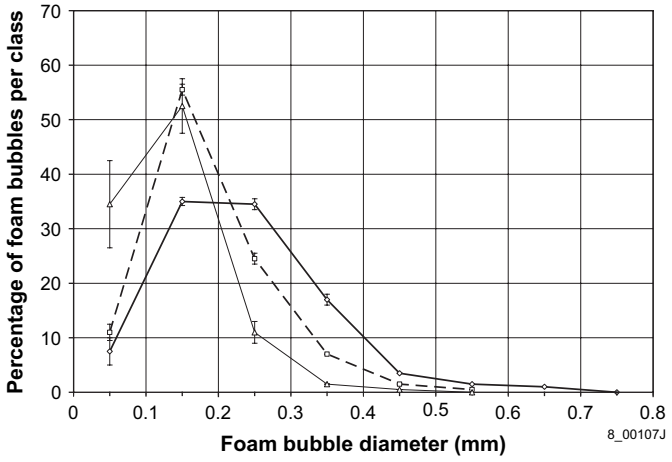

Fig. 3. Bubble size distribution of foams prepared from homogenised and HTST-heated whole milk with dependence on the foaming temperature after 1 min of drainage. Bubble diameter x means class from $x - 0.05$ mm to $x + 0.05$ mm. Results listed are mean values and standard deviations of three analyses; —— 40 °C; – – – 50 °C; —— 60 °C.

One key question is whether the large influence of temperature on foam properties of whole milk is related mainly to the skim milk phase. To approach an answer, it might be helpful to consider the results of Borcherding, Lorenzen, Hoffmann, and Schrader (in press). They used HTST-heated skim milk and identical foaming conditions. The resulting foams prepared between 4 and 20 °C were also unstable and collapsed within a few minutes. Foams prepared between 30 and 60 °C were stable up to 20 min. The highest initial foam density (0.22 g/cm^3) and the smallest foam bubble diameter after 20 min of storage ($d_{10} = 0.27$ mm) resulted at 60 °C. Corresponding to whole milk, the foam prepared at 10 °C had a higher density (0.19 g/cm^3) than the remaining foams. Also, drainage of the foams prepared at 50 and 60 °C increased from about 20 g/100 g after 1 min to about 80 g/100 g after 20 min. In summary, the properties of foams prepared from skim milk and whole milk seem to be similar. This indicates that the fat globules in homogenised whole milk were obviously of minor importance for the foaming properties of the product, but may deteriorate them at certain unfavourable foaming temperatures (20 and 30 °C). Therefore, the skim milk phase containing the milk protein fractions seemed to be mainly responsible for the foaming properties. As mentioned above, the main objective of this study was not to identify the most relevant protein fractions for foaming.

At 40–60 °C, the milk proteins showed an accelerated diffusion and adsorption velocity favouring the formation of smaller foam bubbles (Damodaran & Paraf, 1997; Dickinson, 2003). This process was supported by decreasing apparent viscosity and surface tension values of milk samples with increasing foaming temperatures (Table 1). In addition, higher temperatures led to an increased number of hydrophobic interactions (Erdem, 2006; Jelen & Rattray, 1995). This was due to exposure of hydrophobic groups, which were originally inaccessible inside the globular structures of whey proteins at temperatures below 40 °C (Dupont, 1965; Kella & Kinsella, 1988; quoted from Jelen & Rattray, 1995). The small decrease in pH value as a result of increased foaming temperatures was accompanied with a slightly lower protein net charge and therefore a lower electrostatic repulsion. This resulted in a denser structure of the proteins at the air–water interface (Damodaran, 2005). However, during aging of the foam the continuous drainage led to film thinning, rupture of the lamella and coalescence of bubbles.

3.2. Influence of whole milk homogenisation

Whole milk was pumped through the double-stage homogenisation device and subsequently HTST-heated. The resulting average volume-moment (d_{43}) and volume-surface diameters (d_{32}) are presented in Table 2. The variable d_{32} was necessary for the calculation of the specific fat globule surface ($S_v = 6/d_{32}$). On condition that the protein load is approximately 10 mg/m^2 fat globule surface (Walstra, van Vliet, & Kloek, 1995), about 27% of the protein in the whole milk (3.45 g/100 g) was adsorbed at the interface of the air bubbles after a homogenisation with 250/50 bar was performed. A single-stage homogenisation with 50 bar (no additional pressure in the second stage) demanded for only half of this protein quantity. The milk samples were foamed at 50 °C. Surprisingly, the density of the foams (0.15–0.20 g/cm^3) showed no clear tendency in relation to the homogenisation pressure applied. The same was valid for the results of drainage after either 1 or 20 min. Fig. 4 represents the corresponding distribution of the air bubble sizes of foams of non- and strongly (250/50 bar) homogenised whole milk. After 1 min, most bubbles had a diameter between 0.1 and 0.2 mm. Less than 5% had a diameter above 0.4 mm. After 20 min, most of the air bubbles had a diameter between 0.2 and 0.4 mm, but about 45% of the bubble sizes were above 0.4 mm. All in all, the effect of varying fat globule sizes in whole milk on foam formation and stability of foams prepared at 50 °C was marginal. Apparently, there was sufficient milk protein available to ensure fast and comparatively stable adsorption at the air–serum interface. As far as we know, comparable studies have not been

Table 2
Effect of homogenisation on particle size and calculated characteristics of HTST-heated whole milk

Homogenisation pressure (bar)	Average particle diameter[b]		Calculated specific fat globule surface S_v[c] (m^2/kg)	Estimated proportion of adsorbed protein/total protein[d] (g/100 g)
	d_{43} (μm)	d_{32} (μm)		
–	3.06	2.69	84	2.4
50	1.50	0.51	450	13
100/50[a]	0.76	0.36	630	18
200/50[a]	0.44	0.25	890	26
250/50[a]	0.39	0.24	940	27

[a] Double-stage homogenisation: Total pressure/pressure in the second stage.
[b] Measurements were carried out in duplicate.
[c] S_v = surface of dispersed phase/volume of dispersed phase = $6/d_{32}$; $\rho_{Fett} = 0.93$ g/cm^3.
[d] Calculation according to Walstra, van Vliet, and Kloek (1995): ≈10 mg/m^2 fat globule surface; milk protein content: 3.45 g/100 g.

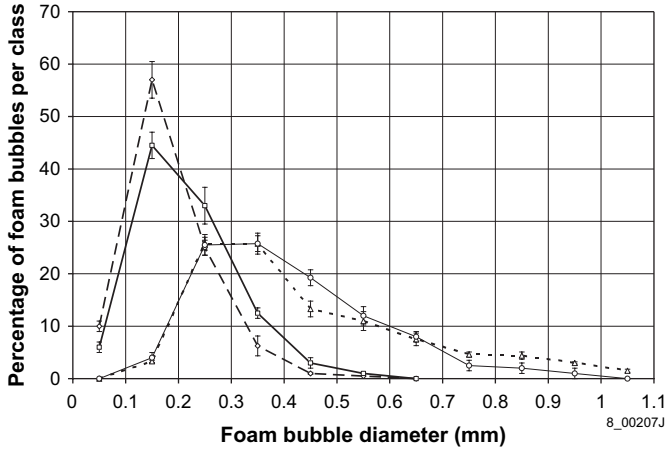

Fig. 4. Bubble size distribution of foams prepared from homogenised (250/50 bar) and non-homogenised HTST-heated whole milk after 1 and 20 min of drainage. Bubble diameter x means class from $x - 0.05$ mm to $x + 0.05$ mm. Results listed are mean values of three analyses and standard deviations; – – – 0 bar/1 min; —— 250/50 bar/1 min; - - - - - 0 bar/20 min; —— 250/50 bar/20 min.

published. Finally, the influence of milk fat globules on the microstructure of the milk foams was studied in more detail.

3.3. Microstructure at air–serum interface

The particle size distribution of the homogenised (200/50 bar) and HTST-heated whole milk before foaming at 50 °C as well as the distribution of the drained liquid after foaming was measured by laser diffraction. Virtually no difference could be detected between the results of the processed milk and the collected drainage up to 20 min after foaming. On the other hand, the not-drained remaining lamellar liquid of the foam showed continuously growing aggregates with a diameter up to 100 μm (Fig. 5). Additional fluorescence microscopy proved that numerous fat globules (vivid yellow by Nile red) were enclosed (Fig. 6).

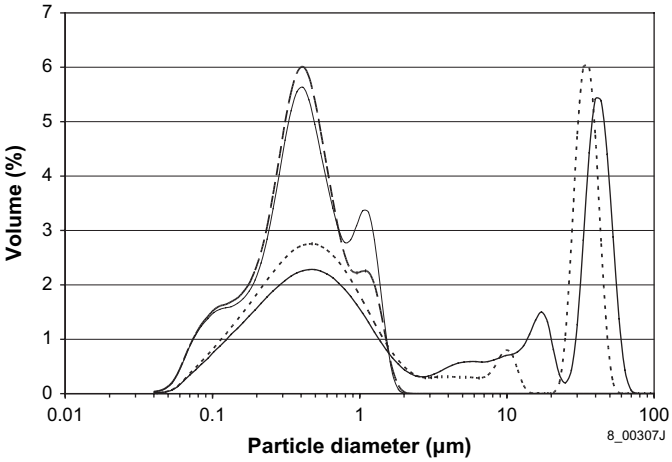

Fig. 5. Volume-related particle size distribution of homogenised and HTST-heated whole before foaming and of the lamellar liquid 1, 10 and 20 min after foaming at 50 °C. Results listed are mean values and standard deviations of three measurements; - - - - - before foaming; —— 1 min after foaming; — — 10 min after foaming; —— 20 min after foaming.

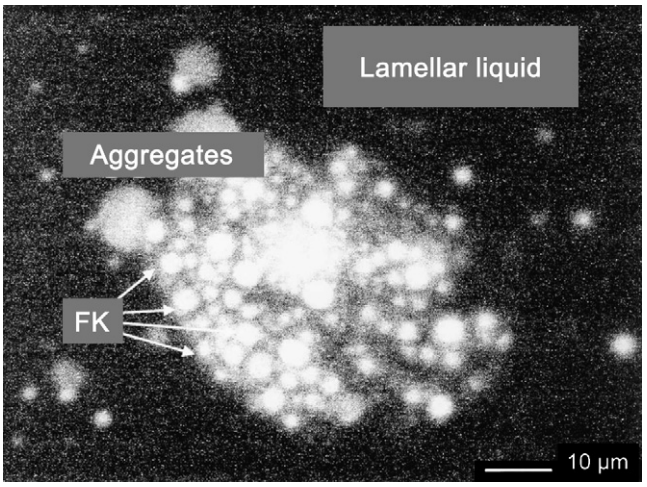

Fig. 6. Fluorescence microscopic image of a fat aggregate in the lamellar liquid of a foam prepared at 50 °C from homogenised and HTST-heated whole milk; FK = fat globules (yellow, converted to greyscale).

The mechanism of the aggregate formation and its microstructure still needs further clarification. Continuous but slow stirring of the liquid for 3 h and thinning with deionised water did not brake up the aggregates. This induces a considerable cohesion of the aggregate structure. The aggregates in Fig. 6 look like protein/lipid aggregates in evaporated milk (Hoffmann, Kiesner, & Schrader, 1998). These aggregates of fat globules and attached casein were mainly the result of the high thermal load during product manufacture and of protein as well as calcium enrichment after water evaporation. Addition of Ca chelating agents such as sodium citrate or EDTA dissolved these aggregates and intact single fat globules remained. The removal of calcium led to a disintegration of the globule-surrounding casein and an increase of serum casein. Corresponding experiments should be carried out with the not-drained lamellar liquid of the foam. Whereas the increase of dry matter during the production of condensed milk occurred by water evaporation, the increase of foam dry matter was a result of continuous drainage. A second distinguishing mark is the high heat load of the condensed milk and the relatively low thermal load of the foam. Therefore, a different mechanism of aggregate formation is to be assumed. Fig. 6 indicated that the fat globules are obviously still intact inside the aggregate. The surrounding material may consist of accumulated interface material but also of different protein fractions which were not attached to the interface.

TEM images of newly prepared foams showed that the membrane of fat globules very close to the bubbles was partially disrupted and liquid fat spread out on the surface of the air bubbles (Fig. 7). Fat globules with intact membranes were found in the serum at a distance of not less than 0.5 μm to the interface. Visible proteins (casein micelles and submicelles, denatured whey proteins) were observed near the interface, but presumably they were not directly adsorbed. A similar sight was observed after 20 min of drainage (Fig. 8). Coalesced fat was still adsorbed at the bubble surface.

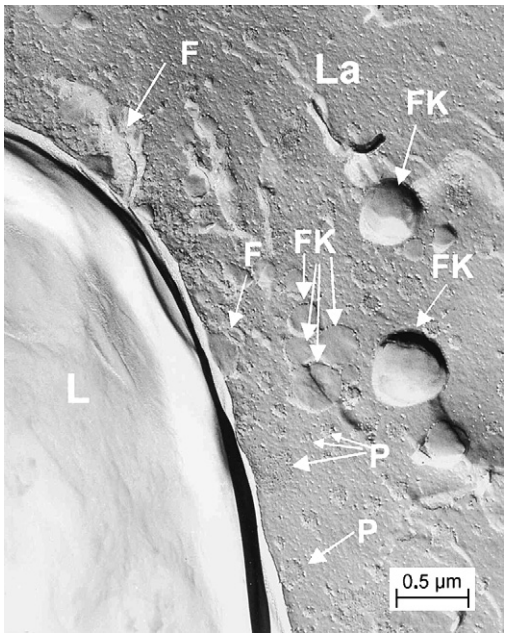

Fig. 7. TEM image of a foam bubble and surrounding lamellae from homogenised and HTST-heated whole milk immediately after foaming (L = air bubble, La = lamella, P = visible protein structure, F = coalesced fat, FK = fat globule).

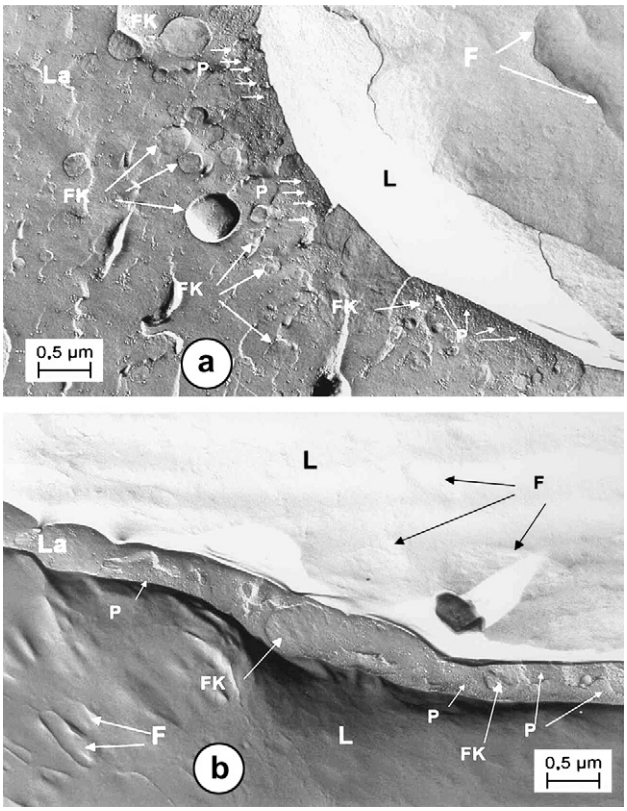

Fig. 8. TEM images (a, b) of foam bubble(s) and surrounding lamella from homogenised and HTST-heated whole milk 20 min after foaming (L = air bubble, La = lamella, P = visible protein structure, F = coalesced fat, FK = fat globule).

Proteins, probably casein submicelles and denatured whey proteins, were identified again close to the interface, whereas native casein micelles were no longer detectable. The interface itself showed no detailed structures. Therefore, the TEM images indicated that the air–serum interface of whole milk foams mainly consists of protein monomers or oligomers such as native whey proteins or non-micellar casein, which, unfortunately, could not be seen by TEM. A film of coalesced liquid fat partially covered the fat globule surface.

4. Conclusion

The foaming apparatus used operated with a low input of mechanical energy. Therefore, more adsorbing affinity of individual milk proteins was necessary at the air–serum interface as with foaming devices under high energy supply. Most of the proteins were dispersed in the serum phase of the whole milk, only a small portion was part of the secondary membrane of the homogenised fat globules. Under the conditions chosen, whole milk was better suited for foaming between 50 and 60 °C than at lower temperatures. This corresponded with the results of Borcherding, Lorenzen, Hoffmann, and Schrader (in press) which used HTST-heated skim milk and identical foaming conditions. In summary, the effect of foaming temperature on the foaming properties was very similar with skim and whole milk. This indicates that the fat globules in homogenised whole milk were obviously of minor importance for the foaming properties of the product. Therefore, the skim milk phase with the milk protein fractions seemed to be mainly responsible for the foaming properties. However, at unfavourable foaming temperatures such as 20 and 30 °C, the fat globules affected the foaming properties more visibly. It was surprising to learn that fat globule size and resulting total membrane area had only marginal effect on the formation and stability of foam. Obviously, the air–serum interface is predominantly dominated by milk protein fractions.

It may be concluded from our results that a varying but low fat content (0–3.5%) and a varying fat globule size in a pasteurised milk, which was foamed at 50–60 °C with a low mechanical input, had no decisive effect on the foaming properties. The study reveals that the air–serum interface consisted mainly of protein monomers and oligomers, while casein micelles were not directly adsorbed. The fat globule membrane seemed to be partly destroyed near the interface and coalesced liquid fat formed a restricted film on the bubble surface that was apparently of minor importance for the foam properties.

References

Anderson, M., & Brooker, B. E. (1988). Dairy foams. In E. Dickinson, & G. Stainsby (Eds.), *Advances in food emulsions and foams* (pp. 221–255). London: Elsevier Applied Science.

Berger, K. G. (1997). Ice cream. In S. F. Friberg, & K. Larsson (Eds.), *Food emulsions*, (3rd ed.). (pp. 413–490) New York: Marcel Dekker.

Besner, H., & Kessler, H. G. (1998). Interfacial interaction during the foaming of non-homogenized cream. *Milchwissenschaft, 53*(12), 682–686.

Borcherding, K., Lorenzen, P. Chr., Hoffmann, W., & Schrader, K. Effect of foaming temperature and varying time/temperature-conditions of pre-

heating on the foaming properties of skimmed milk. *International Dairy Journal*, in press. doi:10.1016/j.idairyj.2007.11.016.

Brooker, B. E. (1985). Observation on the air–serum interface of milk foams. *Food Microstructure, 4*, 289–296.

Brooker, B. E. (1990). The adsorption of crystalline fat to the air–water interface of whipped cream. *Food Structure, 9*, 223–229.

Brooker, B. E. (1993). The stabilization of air in foods containing fat – a review. *Food Structure, 12*, 115–122.

Brooker, B. E., Anderson, M., & Andrews, A. T. (1986). The development of structure in whipped cream. *Food Microstructure, 5*, 277–285.

Buchheim, W. (1991). Mikrostruktur von aufschlagbaren Emulsionen. *Kieler Milchwirtschaftliche Forschungsberichte, 43*, 247–272.

Buchheim, W. (Ed.). (1998). *Ice cream*. Brussels: IDF. [International Dairy Federation Special Issue No. 9803].

Campbell, G. M., & Mougeot, E. (1999). Creation and characterisation of aerated food products. *Trends in Food Science & Technology, 10*, 283–296.

Clarkson, J. R., Cui, Z. F., & Darton, R. C. (1999a). Protein denaturation in foam. I. Mechanism study. *Journal of Colloid and Interface Science, 215*, 323–332.

Clarkson, J. R., Cui, Z. F., & Darton, R. C. (1999b). Protein denaturation in foam. II. Surface activity and conformational change. *Journal of Colloid and Interface Science, 215*, 333–338.

Damodaran, S. (2005). Protein stabilization of emulsions and foams. *Journal of Food Science, 70*, R54–R66.

Damodaran, S., & Paraf, A. (1997). *Food proteins and their applications*. New York: Marcel Dekker.

Dickinson, E. (1992). *An introduction to food colloids*. Oxford: Oxford University Press.

Dickinson, E. (2003). Interfacial, emulsifying and foaming properties of milk proteins. In P. F. Fox, & P. L. H. McSweeney (Eds.), *Proteins* (3rd ed.). *Advanced dairy chemistry, Vol. 1* (pp. 1229–1260) New York, NY: Kluwer Academic/Plenum Publishers.

Dupont, M. (1965). A study of reversibility in the thermodenaturation of bovine β-lactoglobulin A. *Biochimica et Biophysica Acta, 102*, 500–513.

Erdem, Y. K. (2006). Modification of casein micelle structure caused by ultrafiltration and heat treatment: a spectrofluorimetric and kinetic approach. *Journal of Food Engineering, 74*, 536–541.

Fains, A., Bertrand, D., Baniel, A., & Popineau, Y. (1997). Stability and texture of protein foams: a study by video image analysis. *Food Hydrocolloids, 11*, 63–69.

German, J. B., & Phillips, L. (1994). Protein interactions in foams: protein-gas phase interactions. In N. S. Hettiarachchy, & G. R. Ziegler (Eds.), *Protein functionality in food systems* (pp. 181–208). New York: Marcel Dekker.

Goff, H. D. (1997). Colloidal aspects of ice cream. *International Dairy Journal, 7*, 363–373.

Goff, H. D. (2003). Ice cream and frozen desserts. Manufacture. In H. Roginski, J. W. Fuquay, & P. F. Fox (Eds.), *Encyclopedia of dairy sciences*. London: Academic Press.

Graham, D. E., & Phillips, M. C. (1976). The conformation of proteins at the air–water interface and their role in stabilizing foams. In R. J. Akers (Ed.), *Foams* (pp. 237–256). London: Academic Press.

Halling, P. J. (1981). Protein-stabilized foams and emulsions. *CRC Critical Review Food Science Nutrition, 15*, 155–203.

Hinrichs, J. (1994). *Die mechanische Stabilität von Fettkugeln mit kristallinem Fettanteil im Strömungsfeld – Verfahrenstechnische Einflußgrößen und technologische Veränderungen*. [VDI-Fortschrittsberichte Reihe 3 Nr. 368]. Düsseldorf: VDI-Verlag.

Hoffmann, W., Kiesner, C., & Schrader, K. (1998). Effect of technology on protein–lipid interactions in evaporated milk. *Polish Journal of Food and Nutrition Sciences, 7/48*(No 3 (S)), 96–101.

Hoffmann, W., Wieczorek, A., & Borcherding, K. (2002). Untersuchung zur Bildung und Stabilität von Milchschaum. *Kieler Milchwirtschaftliche Forschungsberichte, 54*, 243–255.

Houška, M., Adam, M., Celba, J., Havliček, Z., Jeschke, J., & Kubešová, A., et al. (1994). *Milk, milk products and semiproducts. Thermophysical and rheological properties of foods*. Prague: Institute of Agricultural and Food Information.

Jelen, P., & Rattray, W. (1995). Thermal denaturation of whey proteins. In P. F. Fox (Ed.), *Heat-induced changes in milk* (2nd ed.). (pp. 66–80) Brussels, Belgium: International Dairy Federation.

Kella, N. K., & Kinsella, J. E. (1988). Enhanced thermodynamic stability of β-lactoglobulin at low pH – a possible mechanism. *Biochemical Journal, 255*, 113–118.

Kinsella, J. E., & Phillips, L. G. (1989). Structure function relationships in food proteins. In J. E. Kinsella, & W. G. Soucie (Eds.), *Food proteins* (pp. 52–77). New York: Glenview.

Leser, M. E., & Michel, M. (1999). Aerated milk emulsions – new microstructural aspects. *Current Opinion in Colloid & Interface Science, 4*, 239–244.

Mulder, H., & Walstra, P. (1974). *The milk fat globule. Emulsion science as applied to milk products and comparable foods*. Pudoc, Wageningen, Netherlands: Commonwealth Agricultural Bureaux, Farnham Royal.

Prins, A. (1986). Some physical aspects of aerated milk products. *Netherland Milk Dairy Journal, 40*, 203–215.

Rahn, O. (1922). Die Bedeutung der Oberflächenspannungserscheinungen für den Molkereibetrieb. *Kolloid-Zeitschrift, 15*, 341–346.

Ralet, M.-C., & Gueguen, J. (2001). Foaming properties of potato raw proteins and isolated fractions. *Lebensmittel-Wissenschaft und – Technologie, 34*, 266–269.

Schrader, K., Buchheim, W., & Morr, C. V. (1997). High pressure effects on the colloidal calcium phosphate and the structural integrity of micellar casein in milk. Part 1. High pressure dissolution of colloidal calcium phosphate in heated milk systems. *Nahrung, 41*, 133–138.

Siedel, J., & Hesse, A. (1900). Über das Schäumen der Milch bei der Entrahmung mittels Zentrifugen. *Molkerei-Zeitung, 14*, 637–638, 654–656.

Smith, A. K., Goff, H. D., & Kakuda, Y. (2000). Microstructure and rheological properties of whipped cream as affected by heat treatment and addition of stabilizer. *International Dairy Journal, 10*, 295–301.

Stanley, D. W., Goff, H. D., & Smith, A. K. (1996). Texture–structure relationships in foamed dairy emulsions. *Food Research International, 29*(1), 1–13.

Walstra, P., & de Roos, A. L. (1993). Proteins at air–water and oil–water interfaces – static and dynamic aspects. *Food Reviews International, 9*, 503–525.

Walstra, P., van Vliet, T., & Kloek, W. (1995). Crystallization and rheological properties of milk fat. In P. F. Fox (Ed.), *Advanced dairy chemistry – Lipids* (2nd ed.). (pp. 179–211) London: Chapman & Hall.

Waniska, R. D., & Kinsella, J. E. (1979). Foaming properties of proteins: evaluation of a column aeration apparatus using ovalbumin. *Journal of Food Science, 44*, 1398–1411.

Ward, B. E., Goddard, S. J., Augustin, M.-A., & McKinnon, I. R. (1997). EDTA-induced dissociation of casein micelles and its effect on foaming properties of milk. *Journal of Dairy Research, 64*, 495–504.

Yu, M. A., & Damodaran, S. (1991). Kinetics of protein foam destabilization: evaluation of a method using bovine serum albumin. *Journal of Agricultural Food Chemistry, 39*, 1563.