

The role of bubbles in the development of food structure

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Role of bubbles in structure development

Arpita Mondal^{1*} and Keshavan Niranjana²

¹Dr. Arpita Mondal, Research Fellow, Department of Service Sector Management, Sheffield Hallam University, Sheffield, Howard St, S11WB. Email ID:

a.mondal@shu.ac.uk

²Dr. Keshavan Niranjana, Professor, Department of Food and Nutritional Sciences, University of Reading, Reading, RG6 6AP. Email ID: afsniran@reading.ac.uk

Abstract:

Creating aerated food structure is a challenge in culinary art; but creating such structures consistently on an industrial scale is an engineering challenge. Bubbles add novelty and versatility to the visual appearance and mouthful of foods. The foaminess of cappuccino, sponginess of bread, and brittleness or creaminess of aerated chocolates may be attributed to formation of aerated structures. This chapter addresses the development of bubble containing structures in three specific food systems covering a wide spectrum of rheological behaviours exhibited: milk, chocolate and bread. The characteristics of bubble containing structures in milk (foamability, foam stability, overrun), aerated chocolates (density, gas hold up, bubble sizes), and dough and bread (gas free density, specific volume, void fraction, bubble size and number distribution) are discussed and related to the process parameters, which led to the formation of the structure.

1.Introduction

Bubbles add novel structures and distinctive organoleptic properties, depending on the net gas content and bubble size distribution in many food and drink products which include bread, chocolate, ice cream, whipped cream, and dairy based beverages such as cappuccino. While bubbles do not add any calorific value to foods, they do change their texture and mouthfeel by influencing attributes such as foaminess in cappuccino, sponginess in bread and brittleness or creaminess in aerated chocolate. Thus, most aerated products are well accepted and appreciated by the consumers due to their appearance, texture, sophisticated mouth feel, volume, and the rate of release of aroma in case of dairy based coffee beverages. Cognizance of the influence of different processing methods and conditions is an essential step towards understanding bubble formation, its

growth and stabilization, and finally its effect on the cellular structure of food. This chapter discusses the role of bubbles in structure development with reference to three specific food products with widely differing viscosities: milk (low viscous), chocolate (intermediate viscous) and bread (viscoelastic). More specifically, this chapter addresses the incorporation of bubbles by different methods, and highlights the effect of processing conditions on the development and stabilization of bubble containing structures.

2. Bubble Structures in Milk

Milk foam may be considered to be biphasic colloidal systems where gas bubbles, normally air, are dispersed in a continuous milk phase (Walstra, 1989). Foaming properties of milk to form novel structures are important in processing of many dairy-based products that includes whipped cream, ice-cream, or cappuccino-style beverages. Foamed milk adds significant character in the appearance and sensory attributes of milk based coffee beverages (cappuccino, latte, mocha). For example, foams for cappuccinos are required to have a velvety shiny appearance, with small densely packed air bubbles. Milk foam can also be undesirable in case of reconstitution of infant milk powder or formula. Milk foams are colloidal systems where the structure is created by energy input into milk that includes air bubbles, aqueous phase, surface-active proteins and fat. Energy input is required to overcome the interfacial free energy of the system, which increases during foaming because of enlargement of the surface area. Once formed, the coalescence of gas bubbles normally occurs rapidly in order to minimise surface energy and area. However, intrinsically active proteins and fat tend to form a cohesive visco-elastic film around the bubbles which decrease the interfacial tension and act as a barrier to prevent coalescence, which facilitates the formation of small bubbles (Jimenez-Junca, 2011). The foaming properties of milk are usually expressed in terms of foamability and foam stability. Foamability is generally described by the total volume of foam, say in mL, obtained immediately after foaming under controlled conditions (gas flow/level of agitation etc.) and time. The stability of foam is expressed in terms of half-life, which is the time (say, in minutes) taken for the foam to collapse to half its original volume normally under ambient conditions. Overrun is another foam characteristic parameter, which refers to the volume of air incorporated in the foam. Overrun is generally defined as the difference in density between the milk and the foam, divided by the density of the

foam. Therefore, foam overrun increases with decreasing density of the foam, which is commonly associated with more voluminous foams.

Physical stability of foam is pivotal from a selling point of view, as the foam should remain stable throughout the consumption of the beverage. For frothed beverages like cappuccino, the foam should be stable at least for 10–15 min (Huppertz, 2010). In these type of beverages, baristas often create latte art on the surface of the beverage by utilizing the contrast between the milk bubbles and the coffee. A small bubble size in the latte art ensures a bright foam which leads to the sharp visual contrast between the foamed milk and the coffee. Bubble sizes and their distributions also play important roles in developing the final foam structure. Bubble size is mainly influenced by the method and intensity of foaming. Bubbles are generally small and spherical immediately after foaming; they coalesce with other bubbles to become larger and acquire irregular shapes with time, and finally burst (Figure 1). Foam structure generally disintegrates by three possible phenomena: drainage of liquid, coalescence and disproportionation. The density difference between air in the bubbles and the continuous phase along with gravitational force causes drainage of liquid from a foam head into the liquid while air moves upwards (Huppertz, 2010). Coalescence of bubbles occurs because of liquid drainage from the lamella film as two bubbles approach each other leading to film thinning and rupture (Damodaran 2005). Coalescence of gas bubbles leads to a decrease in the number of gas bubbles in the foam whilst increasing their sizes. The spreading of surface-active material also causes thinning and collapse of the liquid film, as a result of which coalescence may occur (Huppertz, 2010). Disproportionation takes place as a result of the transport of gas from smaller to larger bubbles due to the concentration gradient caused by the difference in Laplace pressure between the bubbles of different sizes. Through this process, smaller bubbles shrink as the larger bubbles grow, until the former disappear. A smaller spread in the size distribution of bubbles can reduce the rate of disproportionation.

Foam properties depend on the process conditions under which these are formed and the method employed to produce the foam. Using the same foaming method it is possible to generate foams with diverse properties if the process conditions are changed.

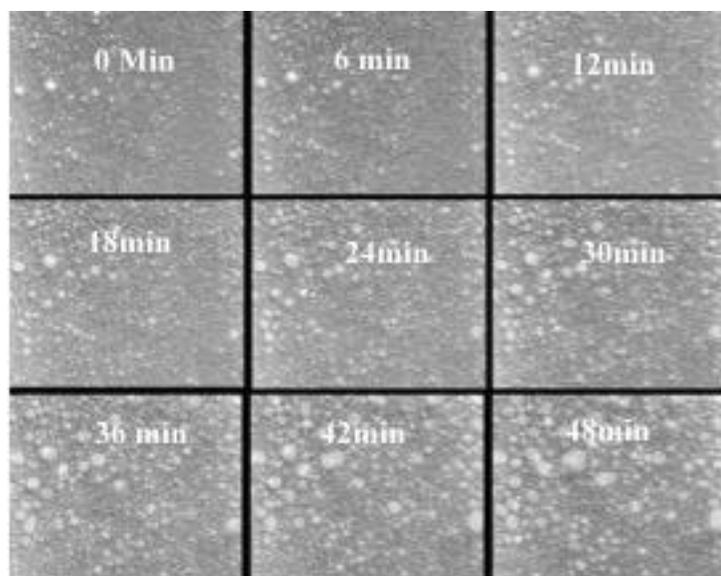


Figure 1: Changes occurring in skim milk foam upon storage at 25°C for up to 48 min following foam formation by agitation. (Copied from Huppertz, 2010)

2.1.Process Parameters

Foaming properties are mainly affected by the biochemical composition of milk, the heat treatment it receives and the temperature during foaming. Different manufacturing conditions and compositions of milk, for example, whole fat milk, low fat milk, reconstituted milk, long shelf life milk, may have different foaming properties.

2.1.1.Milk Protein/ Lipid

Surfactants in milk, for example proteins (high molecular mass surfactants) and polar lipids (monoglycerides and diglycerides, free fatty acids and phospholipids; low molecular mass surfactants) are determining factors of foamability and foam stability. Proteins stabilise foams by forming a visco-elastic film on the surface whereas lipids stabilise foams via the Gibbs–Marangoni mechanism (Huppertz, 2010). Marangoni effect causes rapid adsorption of surfactants from the bulk phase to the areas of lower concentration in the adsorbed film. Marangoni effect allows free lateral diffusion of molecules in the surface layer, allowing rapid equilibration of concentration gradients. Since the stabilisation mechanisms of proteins and polar lipids are mutually incompatible, systems containing both proteins and polar lipids (e.g. whole milk) may show weaker foam stability than systems stabilised by pure compounds (skim milk).

2.1.2.Free Fatty Acid (FFA)

Lipolysis of milk fat by milk lipoprotein lipase results in the release of surface active monoglycerides, diglycerides and free fatty acids (FFAs), all of which are highly detrimental to the formation and stability of milk foams. FFAs in milk are low-molecular-weight surfactants, which compete with milk proteins for adsorption at the air–serum interface of the foams and are capable of displacing proteins from the interface. Adsorption of FFAs leads to disruption of protein–protein interactions, and, as a result, milk proteins are unable to form a stable viscoelastic film around the air bubbles. Weakening of the elastic film around the air bubbles leads to coalescence of bubbles thereby destabilising the foam structure. As FFAs are more surface active than milk proteins, they dominate the air–serum interface at higher concentrations and displace the proteins making the visco-elastic interface weaker. Therefore foams formed from milks with higher FFA content are unstable and coarsen more rapidly when compared to foams formed from milks containing lower FFA content. FFA levels as low as 1 $\mu\text{equiv/mL}$ can have a detrimental effect on the steam foaming properties of milk (Kamath et al., 2008b). Foam stability decreases with an increase in the FFA content. Lower FFA concentration results in the foam remaining smooth and creamy until it reaches its half-life. Good manufacturing practice from cow to consumer has major impact on FFA concentration. In the dairy industry, lipolysis can be induced at any stage of milk processing starting from farm, during transport or in the factory due to agitation and pumping, homogenization, mixing raw and homogenized milk and freezing/thawing of milk (Deeth and Fitz-Gerald, 1995). High-temperature short-time (HTST) pasteurization (72 °C for 15 s) effectively reduces lipolysis and consequent release of FFA by inactivating milk lipase (Deeth, 2006)

2.1.3. Change of pH

Milk pH can influence foaming properties through various mechanisms. Generally milk pH stays in the ‘neutral’ region of pH (6.0–7.0), which has little effect on the foamability, foam stability, overrun, and resistance to drainage and bubble diameter in the case of skim milk foam. If pH is adjusted to more than 7.0, it does not affect the overrun of milk foams, in contrast, it improves the resistance of the foams to drainage, which may be related to the increased viscosity of milk at this pH because of the partial disruption of casein micelles (Borcherding et al., 2009). Microbial growth induces changes in pH or

degradation of fat and proteins. Reduced pH increases the level of non-micellar caseins, calcium and phosphate. When pH is reduced to 5.6, an increase in foamability takes place because of the dissociation, particularly of β -casein, from the casein micelles, which aids rapid and effective covering of the air–water interface (Augustin and Clarke 2008). As pH reduces further to 4.5–5.0, skim milk has very poor foaming properties because of the precipitation of caseins at this pH (Zhang et al. 2004). However, low pH milk has been used only for research studies. In general, low pH can cause coagulation or curdling with a smell and taste of “sour ” in liquid milk.

2.1.4. Skim Milk vs Whole Milk

Casein predominates the foaming behaviour of skim milk, which makes it best in producing voluminous and stable foam. Skim milk foams are quite stable during storage even after 1 hr of producing the foam, where volume of liquid underneath the foamy head steadily increases due to drainage of liquid from the head while foam volume stays same. As a result, bubble size coarsens during storage.

In case of whole milk, fat concentration and physical state affects foam capacity and stability, because the fat can displace the protein from the interface; but when the foaming temperature is above the melting point of fat, it becomes less significant. The foam stability of whole milk can be reduced at low temperature (5-35 °C). This reduction is due to the re-crystallization of globular milk fat. Fat crystals in the globules can pierce foam lamella, resulting in instability. However, the effect of the re-crystallization of globular fat on foam stability decreases as the globular size decreases. Therefore, homogenization techniques, which generate small fat globules, can improve foam stability. Higher the homogenization pressure, higher the bubble count and smaller the bubble sizes, which in turn enhances foaming properties (Huppertz, 2010).

2.1.5. Foaming Temperature

Foaming temperature is the most important process parameter regulating foam structure. Foaming temperature has proportional relationship with foamability, which means the foam volume increases with increasing temperature. It might be due to the fact that both surface tension and viscosity of skim milk decrease with increasing temperature (Kamath et al., 2008a). This causes the proteins present to diffuse to the surface more rapidly and stabilise bubbles more effectively. The mean diameter of bubble in the foam also

decreases with increasing temperature. This is again related to a decrease in surface tension with increasing temperature. All these effects result in foams with higher stability. However, foam volume increases with temperature up to certain level. Foam is more stable at 45-50 °C compared to foam created at 70 °C. Low level of non-micellar caseins and lack of denaturation of whey protein at this temperature could lead to the formation of a strong interfacial layer consisting predominantly of casein micelles.

2.1.6. Influence of Milk Heat Treatment

Heat treatment causes denaturation of whey proteins in skim milk, which is supposed to affect the foaming properties, however, results do not seem to differ a lot. Foamability of pasteurized milk does not vary a lot from UHT-treated skim milk (Kamath et al., 2008a). However, overrun of skim milk foams may increase with increasing heat load applied to the milk due to availability of β -casein, differences in the ionic composition of milk and low concentrations of surface-active peptides (Augustin and Clarke, 2008). Foam Stability of milk is largely unaffected by heat treatment during the first 30 min. During storage, foam stability of heat-treated milk is lower than non-heat treated milk (Huppertz, 2010). Foam stability in pasteurized skim milk between 5–85°C is higher than foams formed in UHT- treated skim milk, under otherwise similar conditions.

2.2. Foam Processing Methods

There are several milk foam processing methods: Steam injection, cold aeration, agitation, super suspension and gas bubbling (Jimenez-Junca, 2011). Steam injection and agitation are most commonly methods employed. Compared to the effects of milk composition and processing conditions on the foaming properties of milk, foams prepared by different methods do not vary markedly (Goh et al., 2009).

2.2.1. Steam Injection

Steam injection has been extensively used in the preparation of the traditional barista-style milk foams in coffee shops. In this method, steam is injected into the milk through small openings in a porous sheet, as a result of which gas bubbles are formed. Steam injection increases of temperature of the milk significantly. Steam injection into a given volume of milk for 50 s increases its temperature to >85 °C; however, the foam temperature does not exceed 65 °C and rapidly decreases to <50 °C within 4 min. Pressure and flow rates are also important factors in injection processes (Junca, 2011).

Figure 2 shows the traditional method of milk frothing by steam injection. Modern machines take advantage of an ejector-type device to restrict the passage of steam and generate the necessary pressure drop to suck air or a mix of air and milk, to generate the foam.



Figure 2: Traditional method of milk frothing by steam injection (Jimenez-Junca, 2011)

2.2.2.Cold Aeration

Similar to steam injection, cold aeration of milk refers to processes where milk is foamed through the incorporation of air, or another gas, at near ambient temperature. In this process, air is forced into the milk through a nozzle or other type of perforated surface, to create small air bubbles, which are rapidly stabilised by the surface- active proteins in milk. Duration of aeration, the gas pressure and the temperature of the milk are main determining factor of foam stability. This method is not commonly used for commercial processes; however it has been widely used in scientific studies (Huppertz, 2010).

2.2.3.Agitation

This method includes stirring, whipping or beating, here the mechanical energy is transferred to the gas-liquid interface, as a result of which bubbles are formed in the liquid. Agitation leads to the initial formation of comparatively large air bubbles, which can be further broken into smaller ones. Some products like whipped cream or ice cream are prepared by this method (Huppertz, 2010). Rotation speed, intensity and duration of agitation and the temperature of the milk are essential variables in whipping process.

Small milk-whisking devices for home use, high-shear mixers and blenders used during the reconstitution of milk powders in the preparation of recombined milk or infant formula falls in this category. A certain angle of the milk foamer (about 50 degree) should be maintained as the tilt angle strongly influences the quality and volume of the foamed milk.

2.2.4.Supersaturation

This process is based on dissolving a gas in a liquid under pressure, thus when the pressure is released, the solubility of the gas is reduced and consequently the bubbles are formed. Aerosol-whipped cream and some milk foams are prepared by supersaturation (Junca, 2011).

Table 1 shows effect of process conditions on foam properties.

Table 1: Effect of process conditions on foams properties (Jimenez-Junca, 2011)

Process variable	Effect on foam properties	Author
Temperature	Heating protein solutions between 60-90 °C increased protein denaturation and decreased the drainage but bubbles were bigger.	(Bals and Kulozik, 2003)
	Milk is better foamed at temperatures greater than 50 °C due to the fat being completely liquefied, although it depends on the fat content	(Borcherding et al., 2008; Kamath et al., 2008a; Silva 2008)
	Direct relationship between foam stability and temperature (21-80 °C) for whey protein but it had a detrimental effect in the case of sodium caseinate.	(Indrawati et al., 2008)
	Preheating whey protein solutions between 70 and 100 °C shows that 80 °C is the optimal temperature to obtain more stable foams with high rigidity	(Nicorescu et al., 2009)
Flow	Increasing the ratio of gas to protein solution flow rates improved the overrun and foam rigidity but the drainage and bubble sizes were greater.	(Bals and Kulozik , 2003)

	Lower flow of protein solution in a whipper increased the formation and stability of foams	(Indrawati et al., 2008)
	Levels of 20 mL/min gas flow rate produced foams with optimum properties in a sparging process using ovalbumin.	(Waniska and Kinsella, 1979)
	Foam drainage was faster and the extent of drainage was greater for larger bubbling flow rates for different protein solutions	(Germick et al., 1994)
Rotor speed	Higher foaming capacity and smaller bubble size was observed at higher whipper speed (5000-15000 rpm).	(Indrawati et al., 2008)
	Viscosity and mixer rotation speed (50-600rpm) were the more important parameters affecting bubble sizes: higher speeds produced lower bubble sizes.	(Balerin et al., 2007)
	Raising the rotational speed (300-1200 rpm) decreased the bubble size and increased the elastic modulus (G') of different dairy emulsions recipes.	(Thakur et al., 2005)
Others	Geometry: using 8 pairs of rotor-stator produced foams with better properties (smaller bubble size and higher overrun)	(Muller-Fischer and Windhab, 2005)
	Container properties: liquid drainage was lower in containers with hydrophobic walls and it was higher when the diameter was increased.	(Papara et al., 2009)

3. Bubble Structures in Chocolate

In this era of calorie conscious consumers, aerated chocolates are well accepted and appreciated due to their sophisticated mouth feel and perceived lower calorie. Bubble inclusion to create aerated chocolate has been practised since 1935 when Rowntree-Mackintosh introduced aerated chocolate as “Aero” in the UK market. Later, Cadbury, Kraft foods, and other brands also launched aerated chocolates. While bubbles do not add

any calorific value to foods, they do change the texture and mouthfeel characteristics such as brittleness or creaminess of the aerated chocolate bar. Bubbles can also help to modulate the flavour and increase the novelty of the product. In contrast to research aiming to understand the role of bubbles in the structure development of low viscosity products (e.g. carbonated beverages, milk based coffee beverages etc.) and high viscosity products (e.g. bread dough), there are relatively fewer studies on intermediate viscous products such as chocolates and cake batter. The quality of aerated chocolates is measured by three parameters: density, gas hold up, and bubble sizes. Gas hold-up is measured by comparing the density of aerated chocolate and gas free density of the liquid or solidified chocolate. Bubble size can be measured by non-destructive, non-invasive X-ray tomography or by other means (Haedelt et al. 2007). Bubble sizes play an important role in characterising mouth-feel. In the context of aerated chocolates, consumer perception can be related to either the smooth mouth-feel of micro aerated chocolate (characterized by the presence of smaller bubbles hardly visible to the unaided eye) or the crispness and brittleness of macro-aerated chocolate (characterized by the presence of larger bubbles) (Haedelt et al. 2007). In practice, differences in bubble sizes and gas hold-up can be created in chocolates by using different gases in the process. The methods employed to include gas bubbles into the chocolate are gas sparging under pressure, vacuum application, extrusion, and reverse phase aeration (Haedelt et al. 2005). Bubble inclusion using different gases under pressure or under vacuum occurs based on the balance between pressure and interfacial forces (Beckett, 2008). If the radius of a bubble is r , the outside pressure on bubble is p_1 and inside pressure is p_2 (as shown in Figure 3), then external force on bubble will be $\pi r^2 p_1$ and inside force in bubble will be $\pi r^2 p_2$. Surface tension (T) also produces the force on circumference of bubble, which can be expressed as $2\pi r T$. In order for the bubble to be stable:

$$\pi r^2 p_1 + 2\pi r T = \pi r^2 p_2 \quad (1)$$

which can be simplified to give the well known Laplace equation:

$$p_2 - p_1 = 2T/r \quad (2)$$

For a given chocolate, smaller bubbles will have higher internal pressure compared to larger bubble. If two bubbles of different sizes come in contact, the gas will move from

high pressure (i.e. smaller bubble) to low pressure bubble (i.e. larger bubble), which will eventually cause coalescence of bubbles.

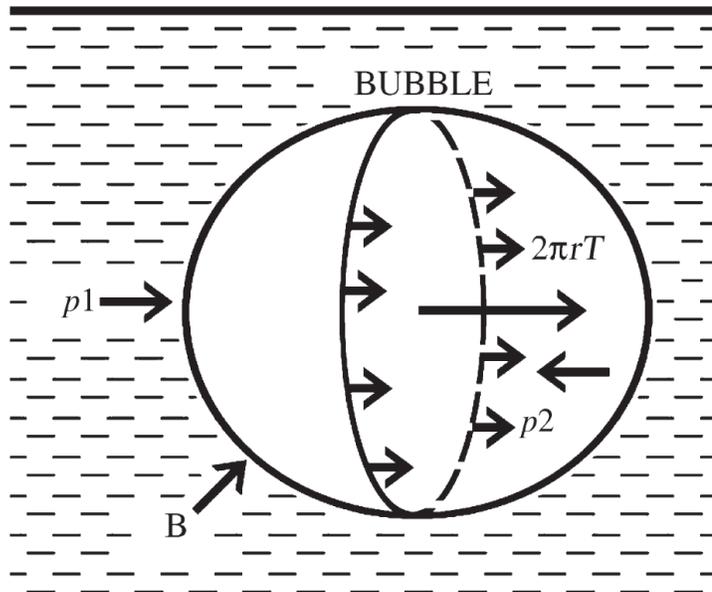


Figure 3: Pressure within a bubble inside chocolate (reproduced from Beckett, 2008)

3.1. Bubble Inclusion Methods

3.1.1. Gas Sparging Under Pressure

In this method, the gas is dissolved and mixed with tempered chocolate under pressure. Then the mixture is exuded through a nozzle when expansion of the mixture causes the gas to come out of the solution thereby forming small bubbles. The chocolate is then deposited in moulds and shaken vigorously to form larger bubbles due to coalescence. The chocolate is then cooled down to solidify and preserve the bubbles. This method produces uniform “thin walled” bubble structure, trapped in viscous chocolate foam, with bulk densities down to 0.4-0.7 g/ml (Jeffery, 1989).

3.1.2. Vacuum application

The vacuum application process consists of mixing gas into melted chocolate suspension, injecting the liquid chocolates into moulds, expanding the bubbles under vacuum, and then cooling immediately to solidify the structure in which bubbles are trapped. Tempering condition (which is required to achieve right type of crystals to stabilize the chocolate foam), vacuum application process and subsequent cooling steps are crucial to get right textured bubble containing chocolate. It is essential that centres of the mould be

properly cooled in order to avoid collapsing. It is obvious that the lower the pressure, higher the gas hold up and fraction of bubble in the chocolate foam. This leads to high levels of coalescence, which further results in larger sized bubbles. This process may produce an aerated centre with a variable size and a reduced bulk density of 0.4-0.7 g/ml from an initial chocolate density of 1.25-1.30 g/ml (Haedelt, 2005). Vacuum pressure can vary from 0.68-0.95 bar, but may also be lower (Jeffery, 1989)

3.1.3.Extrusion

In this method, tempered chocolate is extruded through a die, which incorporates air holes down its length and applying low-pressure air to maintain the structure. This process results in a honeycomb like structure that gives a crisp texture. Extrusion is commonly carried out at ambient temperature where pressure varies from 10-300 bar (Jeffery, 1989). This process is more efficient compared to conventional melting process as the extruded product is capable of maintaining the shape and there is no need for an extra cooling step.

3.1.4.Reverse Phase Aeration

This method consists of dissolving sugar in water and emulsifying liquid chocolate and milk into that (Haedelt, 2005). This mix is then concentrated to adjust the moisture content to 10-12% normally in a continuous scraped vacuum evaporator, then extruded in a vacuum chamber to form bubbles mainly in the aqueous phase. In this method, a stable aerated chocolate is achievable with very low bulk densities between 0.1-0.3 g/ml (Jeffery, 1989).

3.2.Influential Factors in Bubble Inclusion

There are several factors that may influence bubble formation in chocolate. These are classified as intrinsic, extrinsic, system, and operational variables (Massey 2002). Intrinsic factors are attributable to the basic “natural” ingredients of chocolate whereas extrinsic factors are due to those ingredients that are added to the chocolate. System factors are related to the liquid chocolate behaviour (e.g. tempering and rheology) and operational variables (temperature, pressure, type of gas, etc.).

3.2.1.Intrinsic Factors

3.2.1.1.Percentage And Type of Fat

A higher percentage of fat is beneficial for aerated chocolate as it can retain a higher amount of gas. Those types of fat that start crystallizing rapidly, then slow down to allow more gas entrapment are good for bubble inclusion. If the fat is highly polymorphic, for example cocoa butter, it is difficult to control bubble inclusion because the fat continues to crystallize irrespective of cooling rate. Generally, α and β crystals, especially the latter, facilitate inclusion of ample amount of small bubbles (Hui, 1996). Small β crystals are also able to arrange at the interface, to yield a large surface area to volume ratio of fat. These crystals are also slow melting but with fastest setting properties. However, large β crystals result in including larger and fewer bubbles. A high percentage of liquid fat is beneficial for higher gas hold up if crystallization progress continuously. However too much liquid fat can also cause bubbles to burst by spreading over the interface. As cocoa butter replacer, butterfat, palm kernel or coconut oil are good for aerated chocolate as these can be crystallized in β form which reduces densities from 1.3 to 0.2 g/cm³ (Haedelt, 2005).

3.2.1.2.Sugar/Total solid/Moisture

High-grade sugar can significantly vary foaming tendency, for example beet sugar has higher foam value than cane sugar (Minifie, 1989). Also refined sugar is preferable for better aeration. Total solid and moisture content of chocolate are also important intrinsic factors for bubble inclusion as these are able to influence the viscosity of chocolate considerably.

3.2.2.Extrinsic Factors

3.2.2.1.Emulsifiers

Emulsifiers influence the degree of aeration and rheological properties of chocolate by reducing the interfacial tension. They can also influence the crystal structure of fats and alter setting properties. A combination of polyglycerol polyricinoleate (PGPR) and lecithin are used for better bubble inclusion in chocolate (Asama et al. 2000). Lecithin and glycerol monostearate (GMS) can reduce the density up to 0.2g/ml during bubble inclusion (Jeffery, 1989).

3.2.2.2.Tempering

One of the most important steps in chocolate processing is tempering. Chocolate should be correctly tempered to form the crystals which help to stabilize the chocolate. This step

is also significant as it affects the amount of gas dissolved in the chocolate and the viscosity that is required to hold the gas bubble (Haedelt, 2005).

3.2.2.3. Type of Gas

The amount of gas dissolved in the fat phase of chocolate varies with type of gas and pressure and mixing control. Air and most of the gases dissolved in fat phase get released during cooling, except carbon di-oxide, which remains dissolved even at low temperature (Heemskerk, 1990; Wan 1991). Carbon di-oxide and nitrous oxide are able to form larger bubbles with thin lamellae compared to nitrogen and argon (Haedelt et al. 2007). Chocolates made with argon and nitrogen were perceived to be harder, less aerated, slow to melt in the mouth, and having a higher overall flavor intensity (Haedelt et al. 2007). The mixing method employed, percentage of gas mixed, nozzle size, gas flow rate and the mixing head space, all these factors are equally important to get a good dispersion and uniform bubble size in good quality of bubble containing chocolate.

3.2.3. System Factors

3.2.3.1. Viscosity

Cocoa butter exhibits Newtonian flow properties, but with the inclusion of cocoa solid, sugar, milk solid, it becomes a non-Newtonian suspension, which exhibits a yield value and plastic viscosity (Beckett, 2008). Yield value influences bubble stability, especially when chocolate is made under vacuum, whereas, plastic viscosity is more critical for bubble growth when aerating under pressure. The rheology of aerated and un-aerated chocolates is also influenced by other important intrinsic and extrinsic factors (for example temperature, moisture content, particle size distribution, conching time, fat or solid content, emulsifiers, vibration) as these factors influence yield value and plastic viscosity.

3.3. Operational Variables

3.3.1. Mixing Head and Speed in Continuous Process

Mixing speed and volume of mixing head play a vital role in creating a bubble containing chocolate dispersion. The type of mixer influences the energy input. The higher the mixing speed, the lower the bubble size; however, if the speed is low, the required texture of aerated chocolate will not be achieved (Hanselman and Windhab, 1998). The mixer should have high mixing efficiency but with sufficient cooling rate to decrease the

possibility of de-tempering, which may take place due to viscous heat dissipation during mixing (Luiten, 1993).

3.3.2. Fluid and Gas Flow Rate

Bubble size may increase with increased fluid flow rate or decrease with stronger shear. Increased gas flow rate results in larger bubble. When gas is introduced into the liquid inside a mixing head operating under pressure, it dissolves. When the pressure is released, bubble nuclei form and eventually coalesce to form larger bubbles. However, when gas flow is more than an optimum value, the mixer will be unable to disperse all the gas, which may result in the formation of heterogeneous foam (Balerin et al., 2004).

4.3.3. Effect of Vibration

Mechanical vibration plays influential role in bubble containing chocolate. It may either retard or enhance the bubble numbers. Low oscillation reduces chocolate viscosity, thereby, increases bubble rise velocity (Morey, 2000). Frequency and amplitude of vibration control plastic viscosity and yield value of liquid chocolate. For the aerated chocolate, mechanical vibration is generally conducted in the horizontal direction to spread chocolate and to reduce the loss of trapped gas bubble by applying shear force which overpowers yield value and reduces plastic viscosity.

4. Bubble structures in dough and bread

Gas bubbles contribute 70% of bread's final volume (Trinh et al., 2015). Bubbles, which are initially created during mixing of ingredients by trapping air, contribute to bread's appeal through a number of distinctive quality characteristics such as its volume, brightness, shape, texture, and organoleptic properties. When flour and water are mixed to develop dough, wheat protein gluten forms a viscoelastic network that is capable of trapping and retaining gas bubbles. A series of aeration processes take place during baking starting from mixing, then proving to baking. These initial bubbles incorporated initially divide into numerous nuclei as mixing continues and are inflated by carbon-dioxide produced during fermentation (Campbell and Mougeot, 1999). As bubbles are intrinsically unstable, a film of dough confines each bubble in a manacle and protects it from coalescing. These are assumed to be the main features responsible for the typical cellular structure of the bread as well as for the softness of the final product. After going

through several fundamental and complex physical processes (evaporation of water, volume expansion, gelatinization of starch, denaturation of protein, crust formation etc.), gas bubbles settle into the sponge structure and stabilize the internal pressure in breads with atmospheric pressure and protect it from collapsing after taking out of the oven. It is necessary to understand the different processing steps in order to gain insights into the formation of the cellular structure of bread.

4.1. Bubble inclusion Steps

4.1.1. Mixing

Mixing is an important step in baking where dough structure forms by homogenization of the ingredients (such as flour, water, fats, saccharides and yeast) by mixing and hydration of flour particles. The aeration during this step and rheological properties of dough critically influence the gas cell structure in the bread (Chin and Campbell, 2005a). During mixing, wheat protein gluten forms a viscoelastic network with a potential for trapping and retaining gas bubbles. As mixing progresses, gas bubbles disperse into discrete cells within a semi-solid starch-protein matrix. Retention of this structure is important to produce bread with high specific volume. An estimated 10^{11} to 10^{13} gas nuclei are required to obtain a light bread with an even crumb texture (Gan et al., 1995). Mixing causes rheological changes of dough by altering gluten viscoelastic network. Larger loaf volume depends on stretchability of the dough, as dough strain-hardens during stretching (Dobraszczyk et al., 2003). It is assumed that with the hardening up, dough limits the growth of bubbles, thus reduces coalescence between bubbles and ultimately result in greater loaf volumes. Mixing speed and work input must be above a threshold value to develop the optimum gluten network to hold bubbles. As mixing progresses, there is increasing build-up of air in the dough that peaks at a certain value of work input before decreasing. Chin and Campbell (2005a) defined Dough Inflation System point of peak dough development (DIS-PDD). The DIS-PDD mixing time specifies the point at which the optimized gluten network is achieved for maximum bubble stability during subsequent proving and baking. Mixing at higher speeds always gives greater aeration. Higher work input increases strain-hardening index, failure strain and failure stress initially, followed by a decrease. Dobraszczyk et al. (2003) determined degree of strain hardening using exponential relationship of stress-strain:

$$\sigma = ke^{n\varepsilon} \quad (3)$$

where σ is the stress, ε the Hencky strain, k is the coefficient, while the index n is considered a measure of the degree of strain hardening. Chin and Campbell (2005a) determined the failure strain and failure stress from the bubble failure point, *i.e.* when the dough bubble material fails to sustain the inflation and ruptures. They also found that as the mixing progresses, the strain-hardening index of dough increases up to a maximum, then decreases after peak point as the dough becomes over mixed. However degree of strain hardening achieves its highest value at a combination of higher work inputs and faster speeds. If dough is under-mixed or over-mixed beyond its peak development, then bread of inferior quality is produced.

There is obvious difference in dough quality when it is mixed under low pressure or vacuum instead of at atmospheric pressure. At industry level, at first, dough mixing is done under high pressure to improve oxygen availability, followed by a period of partial vacuum to have a control on the cell size distribution (Elmehdi et al., 2004). Air bubbles are eliminated from the dough if the mixing is done under complete vacuum. Therefore density of dough mixed under vacuum or reduced pressure is greater than the dough mixed under atmospheric pressure.

4.1.2. Proving and Fermentation

Proving is the holding stage between mixing and baking, where the expanded cellular structure of the dough finally forms. Traditionally bakers stop mixing or kneading before peak dough development, and the endpoint of mixing is usually identified by visual observation based on experience. However gluten network continues to form during proving. Additionally, shaping before fermentation induces mechanical stress, which may also contribute to gluten network formation. Air bubbles, incorporated during mixing in this network, act as nucleation sites for leavening gases to collect and thus expand the dough. The fermentation process in the dough by the yeast occurs in two main reaction steps, the first one is amylase activity and the second is maltose consumption by the yeast. Amylase transforms maltose into glucose and yeast produces carbon dioxide by consuming glucose during fermentation. Nuclei formed during the mixing stage expand with the accumulation of carbon-di-oxide produced by fermentation and subsequently desorbed from the liquid phase. Moderate increase in fermentation temperature increases

the formation of gaseous carbon dioxide due to increased fermentation rate as well as decrease in carbon dioxide solubility in water (Chiotellis and Campbell, 2003). Generally, in this stage, the bubble numbers and the dough volume gradually increase in a sigmoid-like fashion, i.e., gradually at the beginning of fermentation and more rapidly in the latter stages. The final result is an increase in the specific volume of the loaf with the gas constituting a significant volume. As bubbles further expand, the chance of coalescence between bubbles increases.

4.1.3. Baking

During baking, bubble expands further due to increase of vapour pressure and initially also to increased rate of carbon dioxide production. After certain temperature, yeast activity along with the metabolic reactions terminates. Therefore, new carbon dioxide production ends and with it the associated dough rise also ends. Starch gelatinizes and dough progressively losses water in the forming crust region. The thickness of the formed crust is proportional to dough porosity, i.e., the crust formed on the porous dough is thicker than the crust formed on the compact dough (Bajd and Serša, 2011). Eventually, gas bubbles fracture to stabilize the internal pressure in breads with the atmospheric pressure. This is why breads do not collapse when taken out of the oven.

4.2. Physical and chemical controlling factors

4.2.1. Types of flour

Production of spongy crumb structure requires the dough to be able to retain the air that is entrapped into discrete gas cells during mixing and gas formed during yeast fermentation over extended periods. Wheat flour is extensively used in bread making due to its unique ability to stretch and retaining capacity of bubbles. Elasticity of this flour plays an important role in developing larger loaves. For example, the high protein North American wheat flour is extensively used in bread baking for its high elasticity (Chakrabarti-Bell et al., 2014). Dough of higher elasticity prevents coalescence of bubbles by maintaining thickness of the dough layer more effectively. While, in dough with lower elasticity, bubbles grow and coalesce rapidly as the dough layer weakens more quickly (Chakrabarti-Bell et al., 2013). Strong flour has greater void fraction, bubble size distribution, strain hardening index, failure strain and failure stress compared to weak dough (Bellido et al., 2006). In the case of whole wheat flour, the bran and germ tend to

decrease loaf volume of the dough, and increase crumb firmness and darkening to give different flavour profiles. Additional fibres dilute gluten and distort the gluten-starch network formed during mixing (Pham et al., 2007).

4.2.2. Gluten

The unique wheat protein “gluten” plays an important role in maintaining gas bubble structure in bread (Gan et al., 1995). In cereal industry, flours with high gluten content are conventionally used for baking. A series of shearing, compressing and stretching stages during mixing stage after initial homogenization leads to form gluten network. Gluten-starch matrix provides the framework for gas cell expansion. If gluten is too weak it can't stretch in thin films around the air bubbles produced during fermentation. The gas bubbles would then swell and burst, causing the loaf to lack volume. If gluten is too strong then it won't stretch so the gas bubbles can't expand causing a very dense loaf. Also during the mixing stage, extra “shear” can impair gluten network and thus retaining gas bubble structure (Peighamardoust et al., 2010).

4.2.3. Water Absorbance (WA)

Water Absorbance (WA) of flour also plays very important role in determining loaf volume of the dough (Huang et al., 2016). If the WA of flour is higher, it develops soft dough, which is unable to hold the gas cellular leading to the cell merging during proofing and thus decreases the loaf volumes. Whereas, lower WA can develop hard dough as gluten network cannot be formed without enough water absorption, which eventually leads to the incapability to hold air during fermentation, which also caused the decreased loaf volume of the bread. Therefore optimized water absorbance capacity of flour is very important in developing gluten network for perfect bubble formation in the dough. WA for whole wheat flour ranges from 60.0 to 65.0 g/100 g (Huang et al., 2016).

4.2.4. Yeast/non-Yeast:

Yeast (*Saccharomyces cerevisiae*) is widely used as leavening agent in baking industry. It causes fermentation, which transforms a dense mass of dough to a well-risen loaf. Furthermore, yeast also helps to strengthen and develop gluten in dough and specially contributes to distinct flavours in bread. Different types of bread with variable yeast and water contents can cause distinct cellular structures in bread (Lampignano et al., 2013). With constant flour content, percentage volume of bubbles increases to a certain value

with increasing yeast amount, after which it stabilizes regardless of the increment in the quantity of yeast added. This happens as carbon-di-oxide production rate is strictly related to the metabolism of the yeast with the consumption of the simple sugars present in the flour. As the flour quantity is kept constant so is the amount of simple sugars present in the flour and also the water content, it is therefore not surprising that percentage pore volume expansion reaches a maximum value even though the yeast amount increases. Subsequently, in the final dough-rise step, high amount of yeast may lead to a collapse in the structure of the cell walls and an associated loss in product quality. For non-yeasted dough, chemical leavening systems are used to raise the volume by evolving carbon dioxide, though they are unable to create the unique flavour of yeast fermented bread.

4.3.Characterization of bubble in bread

Aerated texture of the bread is primarily quantified by the gas bubble characteristics (such as gas free density, specific volume, void fraction, bubble number and distribution characterize dough aeration) of the dough.

4.3.1.Gas free density

Explicit measurement of these properties is not a straightforward task and it requires specialized equipment to measure. Campbell et al. (2001) first introduced a dynamic dough density (DDD) apparatus, where differences in the buoyancy of dough in xylene are used to monitor dough expansion as a function of time during dough fermentation. Using this apparatus, Chin and Campbell (2005a) determined the gas-free dough density, ρ_{gf} , by extrapolating the graph of dough density *versus* mixing pressure (P) to zero absolute pressure and fitting a regression line to find the intercept.

$$\rho = \rho_{gf} - sP \quad (4)$$

where ρ is the dough density, s is the slope of graph.

4.3.2.Specific Volume

Specific volume of dough is an important quality control parameter that gives an indication of the final degree of aeration achieved in the dough at the end of fermentation. It is also used to assess of the efficacy of chemical leavening system products. Bellido et al. (2009) measured dynamic specific volume (DSV) in dough, where aeration was controlled over a wide range of rates using various chemicals leavening systems and

processing conditions. Following equation was used to measure specific volume of the dough (Y):

$$Y = \frac{LA}{m} \quad (5)$$

where L is the sample thickness, A is the area of the dough as a function of time, and m is the dough mass.

4.3.3.Void fraction/gas volume fraction/ bubble fraction

Void fraction is another macro property to characterize dough aeration. Void fraction decreases as viscosity of the dough increases. Also, at high void fractions, gas loss takes place due to coalescence of the gas bubbles in the dough. Different gas production capacities of the various leavening systems (yeast/chemical leavening agent) as well as flour type play a prominent role in determining the final void fraction in the dough. For chemically leavened dough gas retention properties of the dough causes differences in the final void fractions. Chin and Campbell (2005b) determined gas void fraction (α_p) using density of the dough, at mixing pressure:

$$\alpha_p = 1 - \frac{\rho}{\rho_{gf}} \quad (6)$$

Bellido et al (2006), on the other hand, determined void fraction of the dough using specific volume of the dough:

$$\phi = 1 - \frac{Y_{gf}}{Y} \quad (7)$$

where ρ is the density of the dough, ρ_{gf} is the density of gas-free dough, Y_{gf} is the specific volume of final gas free dough and Y is the specific volume of the dough at long fermentation time. Chin and Campbell (2005b) found that a 0.5% increase in the gas-free dough density causes 10% increase in void fraction. During baking, the void volume fraction of bread can reach a final value between 0.8 and 0.9.

4.3.4.Bubble size and number distribution

Gas bubbles contribute a significant proportion of bread's volume and thus their size distribution and numbers play an important role in deciding dough rheology, sensory properties, and final texture of the bread (Campbell et al., 1991). For example, standard tin loaf contains numerous small bubbles, whereas baguette bread contains fewer but bigger sized bubbles. The precise size distribution of bubbles in the dough is much more difficult to determine due to its fragile nature. Recent development of imaging techniques

enabled the in situ observation of bubble structure evolution during different stages of baking. Various imaging techniques starting from flatbed scanning and conventional photography to more advanced high-resolution techniques, such as, scanning electron microscopy, X-ray computed tomography and magnetic resonance imaging (MRI) have been extensively used in studies of bread baking (Scanlon and Zghal, 2001).

5. Conclusion

This chapter brings to light the effect of different processing methods and conditions on aerated structure of foods with particular reference to milk based beverages, bread and chocolate. Bubble sizes and their distributions play important roles in developing the structure of such foods. Foaming properties of milk is majorly affected by its biochemical composition and foaming temperature, compared to the foam generation methods employed. Skim milk foams are quite stable and voluminous compared to whole milk. Although aerated chocolate is preferred by consumers, there are relatively fewer studies on the role of bubbles in the development chocolate structures. Differences in bubble sizes and gas hold-up in chocolate can be created by using different gases and different methods. The volumes of gas mixed, mixing methods, nozzle size, gas flow rate and the mixing head space pressures, all these factors critically influence bubble sizes and dispersion characteristics. Carbon dioxide and nitrous oxide are able to form larger bubbles and lighter chocolate, compared to nitrogen and argon which result in harder and less aerated structures. β crystals in cocoa butter facilitate inclusion of small bubbles in chocolate. Correct tempering is a prerequisite to achieving the right structure in chocolates. Bubble structure in bread is mainly affected by processing methods. The aeration during mixing of dough along with the viscoelastic properties of the dough critically influence the spongy structure of bread. Additionally, fermentation during proving and baking also result in increases of the specific volume of the loaf. Flour composition and gluten content also play a determining role in characterising the bubble containing structure. Coalescence, disproportionation, and drainage of water cause disintegration of aerated structure. Microscopic imaging coupled with image analysis can be used to observe the structure evolution and identify the dominant destabilising mechanisms.

References:

1. Asama, K., Yamada, K., Nago, A. (2000). Gas incorporated chocolate and its production. EU patent 124433.
2. Augustin, M. A., Clarke, P. T. (2008) Skim milk powders with enhanced foaming and steam-frothing properties. *Dairy Science and Technology* 88 149–161.
3. Bajd, F., Serša, I. (2011). Continuous monitoring of dough fermentation and bread baking by magnetic resonance microscopy. *Magnetic Resonance Imaging*, 29, 434–442.
4. Balerin, C., Aymard, P., Ducept, F., Vaslin, S., Cuvelier, G. (2004). Influence of formulation and process parameters on foam properties. *International Conference Engineering and Food*, Montpellier, France.
5. Balerin, C., Aymard, P., Ducept, F., Vaslin, S., Cuvelier, G. (2007). Effect of formulation and processing factors on the properties of liquid food foams. *Journal of Food Engineering*, 78, 802-809.
6. Bals, A., Kulozik, U. (2003). Effect of pre-heating on the foaming properties of whey protein isolate using a membrane foaming apparatus. *International Dairy Journal*, 13, 903-908.
7. Beckett, S.T. (2008). *The science of chocolate*. 2nd Edition. The Royal Society of Chemistry publishing. Thomas Graham House, Science Park, Milton Road, Cambridge CB4 0WF, UK.
8. Bellido, G. G., Scanlon, M. G., Page, J. H., Hallgrimsson, B. (2006). The bubble size distribution in wheat flour dough. *Food Research International*, 39, 1058–1066.
9. Bellido, G. G., Scanlon, M. G., Page, J. H. (2009). Measurement of dough specific volume in chemically leavened dough systems. *Journal of Cereal Science*, 49, 212–218.
10. Borcherdig, K., Hoffmann, W., Lorenzen, P.C., Schrader, K. (2008). Effect of milk homogenisation and foaming temperature on properties and microstructure of foams from pasteurised whole milk. *LWT - Food Science and Technology* 41(10):2036-2043.
11. Borcherdig, K., Lorenzen, P. C. Hoffman, W. (2009). Effect of protein content, casein–whey protein ratio and pH value of the foaming properties of skimmed milk. *International Journal of Dairy Technology*, 62, 161–169.
12. Campbell, G. M., Rielly, C. D., Fryer, P. J., Sadd, P. A. (1991). The measurement of bubble size distribution in an opaque food fluid. *Transactions of the Institution of Chemical Engineers, Part C, Food and Bioproducts Processing*, 69, 67–76.
13. Campbell, G. M., Mougeot, E. (1999). Creation and characterisation of aerated food products. *Trends in Food Science & Technology*, 10, 283-296.
14. Campbell, G.M., Herrero-Sanchez, R., Payo-Rodriguez, R., Merchan, M.L. (2001). Measurement of Dynamic Dough Density and Effect of Surfactants and Flour Type on Aeration During Mixing and Gas Retention During Proofing. *Cereal Chemistry*, 78, 272–277.
15. Chakrabarti-Bell S, Wang S, Patel M J, Weiss R M, Austin PJ (2013) Bubbles in chapatti doughs. *Journal of Cereal Science*, 57, 504–513.
16. Chakrabarti-Bell, S., Wang, S., Siddique, K. H. M. (2014). Flour quality and disproportionation of bubbles in bread doughs. *Food Research International*, 64, 587-597.

17. Chin, N. L., Martin, P. J., Campbell, G.M. (2005a) Dough aeration and rheology. II. Effects of flour type, mixing speed and total work input on aeration and rheology of bread dough. *Journal of the Science of Food and Agriculture*, 85, 2194-2202.
18. Chin, N. L., Martin, P. J., Campbell, G. M. (2005b). Dough aeration and rheology: Part 3. Effect of the presence of gas bubbles in bread dough on measured bulk rheology and work input rate. *Journal of the Science of Food and Agriculture*, 85, 2203-2212.
19. Chiotellis, E., Campbell, G.M. (2003). Proving of bread dough I – modelling the evolution of the bubble size distribution. *Transactions of the Institution of Chemical Engineers, Part C, Food and Bioproducts Processing*, 81, 194–206.
20. Damodaran, S. (2005). Protein Stabilization of Emulsions and Foams. *Journal of Food Science*, 70, 54–66.
21. Deeth, H. C., Fitz-Gerald, C. H. (1995). Lipolytic enzymes and hydrolytic rancidity in milk and dairy products. *Advanced dairy chemistry, Volume 2*, 247–308. London, UK: Chapman & Hall Publishers.
22. Deeth, H.C. (2006). Lipoprotein lipase and lipolysis in milk. *International Dairy Journal*, 16, 555-562.
23. Dobraszczyk, B.J., Smewing, J., Albertini, M., Maesmans, G., Schofield, J.D. (2003). Extensional rheology and stability of gas cell walls in bread doughs at elevated temperatures in relation to bread making performance. *Cereal Chemistry*, 80, 218–224.
24. Elmehdi, H.M., Page, J.H., Scanlon, M.G., (2007). Evaluating dough density changes during fermentation by different techniques. *Cereal Chemistry* 84, 250–252.
25. Gan, Z., Ellis, P.R., Schofield, J.D. (1995). Gas cell stabilization and gas retention in wheat bread dough. *Journal of Cereal Science*, 21, 215–230.
26. Germick, R.J., Rehill, A.S., Narsimhan, G. (1994). Experimental investigation of static drainage of protein stabilized foams - Comparison with model. *Journal of Food Engineering*, 23, 555-578.
27. Goh, J., Kravchuk, O., Deeth, H. C. (2009). Comparison of mechanical agitation, steam injection and air bubbling for foaming milk of different types. *Milchwissenschaft*, 64,121–124.
28. Haedelt, J. (2005). An investigation into bubble inclusion into liquid chocolate. *Ph.D Thesis*, School of Food Biosciences, University of Reading, Reading, UK.
29. Haedelt, J., Leo Pyle, D., Beckett, S. T., Niranjana, K. (2005). Vacuum-induced bubble formation in liquid-tempered chocolate. *Journal of Food Science E: Food Engineering And Physical Properties*, 70, 159-164.
30. Haedelt, J., Beckett, S.T., Niranjana, K. (2007). Bubble-included chocolate: relating structure with sensory response. *JFS E: Food Engineering and Physical Properties*, 72, 138-142.
31. Hanselmann, W., Windhab, E. (1998). Flow characteristics and modelling of foam generation in a continuous rotor/stator mixer. *Journal of Food Engineering*, 38, 393-405.
32. Hatakeyama, S., Akiyama, M., Yoneyama, R., Watanabe, K., Koizumi, R., Miyaji, K., Mizota, Y., Ikeda, M., Wakao, S. (2019). Effects of manufacturing conditions on the foaming properties of milk and sensory characteristics of foamed milk. *LWT, Food Science and Technology*, 99, 555-561.

33. Heemskerk, R. (1990). Aerated fat-based compounds-volume for money. *Food marketing and technology*, 4, 54-55.
34. Huang, G., Guo, Q., Wang, C., Ding, H. H., Cui, S. W. (2016). Fenugreek fibre in bread: Effects on dough development and bread quality, *LWT - Food Science and Technology*, 71, 274-280,
35. Hui, Y.H. (1996). *Bailey's Industrial oil and fat products*, New York Chichester: Wiley.
36. Huppertz, T. (2010). Foaming properties of milk: A review of the influence of composition and processing. *International Journal of Dairy Technology*, 63, 477-488.
37. Indrawati, L., Wang, Z., Narsimhan, G., Gonzalez J. 2008. Effect of processing parameters on foam formation using a continuous system with a mechanical whipper. *J Food Eng* 88(1):65-74.
38. Jeffery, M.S. (1989). Aerated/moulded chocolate. *The Manufacturing Confectioner*, 69, 53-56.
39. Jimenez-Junca, C. A. (2011). Foaming of milk by steam injection: Relationships between foaming conditions and foam characteristics. *Ph.D Thesis*, School of Food Biosciences, University of Reading, Reading, UK.
40. Kamath, S., Huppertz, T., Houlihan, A.V., Deeth, H.C. (2008a). The influence of temperature on the foaming of milk. *International Dairy Journal*, 18, 994-1002.
41. Kamath, S., Wulandewi, A., Deeth, H. (2008b). Relationship between surface tension, free fatty acid concentration and foaming properties of milk. *Food Research International*, 41, 623-629
42. Lampignano, V., Laverse, J., Mastromatteo, M., Del Nobile, M.A. (2013). Microstructure, textural and sensorial properties of durum wheat bread as affected by yeast content. *Food Research International*, 50, 369–376.
43. Luiten, R. (1993). Developments in continuous aeration of chocolate products and fat creams. *Food Marketing and Technology*, 7, 40-41.
44. Massey, A.H. (2002). Air inclusion mechanisms and bubble dynamics in intermediate viscosity food systems. *Ph.D thesis*, School of Food Biosciences, University of Reading, Reading, UK.
45. Minifie, B.W. (1989). *Chocolate, cocoa and confectionery-Science and Technology*. New York London, Chapman and Hall.
46. Morey, M.D. (2000). Rheological studies on molten chocolate. *Ph.D thesis*. Birmingham University.
47. Muller-Fischer, N., Windhab, E.J. (2005). Influence of process parameters on microstructure of food foam whipped in a rotor–stator device within a wide static pressure range. *Colloids and Surfaces A: Physicochem Engineering Aspects*, 263, 353-362.
48. Nicorescu, I., Loisel, C., Riaublanc, A., Vial, C., Djelveh, G., Cuvelier, G., Legrand, J. (2009). Effect of dynamic heat treatment on the physical properties of whey protein foams. *Food Hydrocolloids*, 23,1209-1219.
49. Papara, M., Zabulis, X., Karapantsios, T.D. (2009). Container effects on the free drainage of wet foams. *Chemical Engineering Science*, 64, 1404-1415.
50. Patel, M. J., Chakrabarti-Bell, S. (2013). Flour quality and dough elasticity: Dough sheetability. *Journal of Food Engineering*, 115, 371–383.

51. Peighambardoust, S.H., Fallah, E., Hamer, R. J., van der Goot, A.J. (2010). Aeration of bread dough influenced by different way of processing. *Journal of Cereal Science*, 51, 89-95.
52. Pham, V.H., Tomoko, M., Naofumi, M. (2007). Dough and bread qualities of flours with whole waxy wheat flour substitution. *Food Research International*, 40, 273-279.
53. Scanlon, M.G., Zghal, M.C. (2001). Bread properties and crumb structure. *Food Research International*, 34, 841–864.
54. Silva, S. (2008) An investigation into milk foaming by steam injection. [DPhil dissertation]. Reading, UK: University of Reading. 187 p. Available from: University paper copy: THESIS-R10283.
55. Thakur, R.K., Vial, C., Djelveh, G. (2005). Combined effects of process parameters and composition on foaming of dairy emulsions at low temperature in an agitated. *Journal of Food Engineering*, 68, 335-347.
56. Trinh, L., Lowe, T., Campbell, G.M., Withers, P.J., Martin, P.J. (2015). Effect of sugar on bread dough aeration during mixing. *Journal of Food Engineering*, 150, 9–18.
57. Walstra, P. (2003). *Physical Chemistry of Food*. New York: Marcel Dekker Inc.
58. Wan, O.J. (1991). *Properties of fats and oils. An introduction to oils and fats technology*. Champaign, Illinois, American oil Chemists Society:16-49.
59. Waniska, R.D., Kinsella, J.E. (1979). Foaming properties of proteins: evaluation of a column aeration apparatus using ovalbumin. *Journal of Food Science*, 44, 1398-1402.
60. Zhang, Z., Dalgleish, D. G., Goff, H. D. (2004). Effect of pH and ionic strength on competitive protein adsorption to air/water interfaces in aqueous foams made with mixed milk proteins. *Colloids and Surfaces B: Biointerfaces*, 34, 113–121.

