Bubbles in Food: Structure creation out of thin air!

Abstract:

Bubbles have been incorporated into foods for many years, and the structure, texture and mouthfeel of such products have been dominated by the characteristics of the dispersion. Despite longstanding use, bubble incorporation has scarcely been studied as a food processing operation. Likewise, bubbles or gases have scarcely been mentioned as food ingredients in literature. The main aim of this article is to redress this issue by throwing light on the formulations and processes employed to incorporate bubbles into foods to create novel products, structures and mouthfeels. Another key attraction of bubble containing foods is that the structure is created using a zero calorie food ingredient, i.e. air or other pure gases, which gives consumers lower calorie foods and manufacturers significant market advantage. The article also identifies the opportunities and challenges offered by bubble containing foods.

Introduction:

Bubbles are associated with celebration and have excited human beings of all ages - from kids to seniors. In food and drink, bubbles are always perceived to represent the best in terms of novelty, health and luxury! From traditional products such as bread, champagne and ice creams, to more trendy products such as cappuccino and sparkling mineral water, the presence of bubbles dominates our perception of food quality. In recent years, there has been a constant flow of new bubble containing snack foods into our supermarkets – soft cheese, aerated chocolates, wafers, cakes, meringues and a range of extruded expanded products - most of which manage to gain a positive market image because they possess very novel structures and offer novel mouth-feel, whilst offering lighter alternatives in terms of calories. A “gaseous ingredient” is common to all such products, which may be air, steam or other pure gases such as carbon dioxide, nitrogen or helium. It is ironic that most books on food ingredients do not even mention gases as food ingredients, despite their widespread use. This article aims to present an overview of the key features of bubble containing food products, their manufacture, and the science underpinning their structure and stability.
Formation of bubble containing food products:

Bubbles are formed by different mechanisms, depending on the food. In the case of bread, the bubble nuclei are formed during mixing and proving of the dough, predominantly by the action of yeast, which grow during baking to create a highly porous structure (Fig 1) that facilitates oral processing and subsequent digestion. A question often asked is whether the “holes” in a slice of bread are bubbles? Or mere voids? This is a matter of terminology. Each void started life as a bubble – i.e. gas entrapped within a liquid or soft solid – which grows into a stable sized bubble after baking and cooling. A number of such bubbles form a network embedded within a slice to give the slice its structure and a conveniently edible texture.

Fig 1: A slice of bread showing its porous structure

The porous network of extruded and expanded snacks are also formed by bubble growth during extrusion (Fig 2), but this growth occurs spontaneously due to a sudden and sharp pressure drop occurring across the extrusion die. This process is similar to the popping of corn, where water boils into a steam bubble which expands as more water boils and pushes the bubble interface outwards causing the corn to pop. The mechanism of porous structure formation during the baking of cakes is also similar to bread baking, except that it is not purely driven by water evaporating, but also by carbon dioxide release caused by baking powder which is invariably an ingredient added to the cake batter.

It is necessary to note that the shapes of the pores or voids can widely differ between different foods, and sensory preferences can be significantly influenced by shapes. Crumpet is traditionally made by heating fermented batter on a hot plate at around 230°C. The characteristic structure of a good crumpet contains very few regular bubbles; instead, the structure is characterised by the presence of vertical pores which develop rapidly during hot plate baking, more or less within 30s (Pyle, 2005) (Fig 3).
Fig 3: Structure of crumpets: The crumpet structure to the left of this photograph is more desirable on account of the dominance of vertical pores along its thickness, whereas the one to the right does not contain such pores and instead also has a high proportion of regular bubbles. The vertical pores impart a spongy texture and mouthfeel.

The formation of structure in so-called “aerated chocolates” is somewhat different. In this process, the chocolate is melted and tempered, so that the right type of crystals are produced which support bubble formation and stabilisation after sparging air or other gases and cooling (Fig. 4).

Fig 4: Bubbles in Chocolate (Vieira and Sundara, 2011)

The formation of structure and texture in fizzy drinks occur by a different mechanism. Here carbon dioxide gas is dissolved under positive pressure in a flavoured sugar syrup maintained at a low temperature to form a supersaturated solution, and subsequently filled in bottles or other containers and sealed under pressure. The gas is gradually released as fine bubbles, when the container seal is broken and the syrup is exposed to atmospheric pressure. When this bubbly mixture is consumed, the bubbles continue to be released in the mouth possibly at a slightly higher rate because the temperature of the mouth is invariably greater than the temperature at which the drink was stored in the container. The release and subsequent popping of the bubbles in the mouth is one of the reasons why we experience “fizz”. A second concomitant effect is the perceptibly “pleasant irritation” on the surface of the tongue caused by the low pH of the carbonated sugar syrup. Thus, one can postulate that the fizz experienced
is a combination of bubble popping and acid irritation. It is worth noting that our knowledge of the sensory science of bubble containing products, available in the public domain, is very limited and this is an area which badly needs further exploration.

Ice creams contain a significant proportion of air by volume: typically, half a tub of ice cream is air! Since ice cream is invariably sold by volume, a consumer ends up paying for a significant volume of air! Although it is natural to feel somewhat cheated, it is necessary to appreciate that air bubbles are an integral part of the experience of consuming ice creams. The smooth texture and mouthfeel of ice cream is attributable to the right balance between the effects of fat, ice crystals and air bubbles. Without air bubbles, the ice cream is unlikely to possess a smooth mouthfeel. Poorly textured ice creams can be gritty and feel more like ice lollies!

There are a number of other bubble-containing food products some of which are not widely known! For instance, the cream filling sandwiched between biscuits in what are commonly known as cream biscuits, is invariably a bubble containing fat-sugar dispersion. The bubbles are extremely fine and hardly visible to the naked eye, but it is claimed that the bubbles are perceptible and one would notice a different mouthfeel if the cream was merely fine sugar particles dispersed in fat. The texture of a biscuit, itself, may be attributed to the porous structure which causes the biscuit to be brittle, soft or hard. The fracture mechanics of biscuit plays a key role in defining its mouthfeel and indeed in its enjoyment. Wafers used for making ice cream cones, or those incorporated in other applications, are also made from a batter which is aerated. The extent of aeration critically influences the texture, wettability and mouth-feel of the wafer, and it is one of the most critical steps in wafer manufacture.

Most of the above products have pores or bubbles dispersed uniformly throughout their bodies. But there are products – like cappuccino or draft beer – which are presented to a consumer with a foamy head. Given that air has a significantly lower density than water, or any other liquid food, a foam is inherently unstable and creating a head that is stable over the duration of consumption is a challenge. Typically, a cappuccino foam lasts 10-15 mins and one would expect the head on beer to last longer in a typical “social drinking setting”. The milk is foamed in the case of cappuccino, following which a suitable coffee decoction is added. The method of foaming milk is also critical. Generally, the foam - which is created by mechanical agitation in the case of normal “vending machines” – is relatively weak and unstable. However, foams created by steam sparging into milk – which is normally done in modern coffee bars – is significantly richer in texture and lasts longer. In the case of draft beer, the gas lost from the foamy head is constantly replenished by carbon dioxide desorbing from the main body of the beer – which give the head a longer life than cappuccino.

Having gained an appreciation of the features of typical bubble containing food products, we shall now consider the science and technology of aeration.

**Scientific underpinning of the process of food foam formation**

There are two key aspects underpinning the science of bubble containing foods: 1. The method used to produce the bubble containing dispersion and 2. The quality and stability of the resulting foam. There are several methods used to incorporate bubbles in food systems: 1)
Mechanical agitation with or without gas sparging, 2) Steam induced incorporation (Puffing, Frying, Cappuccino making fall in this category), 3) Chemical methods (including the use of chemical raising agents, 4) Biological methods (e.g. fermentation) and 5) Miscellaneous methods (use of aerosols, in-can widget etc). Mechanical agitation can either be performed under positive or negative pressure. The use of partial vacuum to draw bubbles out of a liquid was indeed common practice a few decades ago, but most of the modern process are positive pressure process employing pressures of 5-10 bar. In fact, modern processes are also continuous where the gas and fluid phase enter a mixing head maintained under pressure, and a dispersion leaves the head after the pressure is released back to the ambient value. Mondomix aerator (e.g. https://www.buhlergroup.com/content/buhlergroup/global/en/products/mondomix_vl_aerator.html) – which employs this methodology - is very widely used in industrial practice (see Fig 5).

![Diagram of Mondomix aerator](https://www.buhlergroup.com/content/buhlergroup/global/en/products/mondomix_vl_aerator.html)

**Fig 5:** Photograph of the mixing head of Mondomix (Courtesy Buhler AG)

The quality and stability of the dispersion is characterised in terms of the foam stability if the product is in the fluid state, but if it is a solid product, the properties are determined after solidification. Although a number of properties can be used to characterise a dispersion, the gas hold-up or the volume fraction of the gas is most commonly used. This parameter, denoted by $\varepsilon$, can be easily determined by measuring the densities of the dispersion and the unaerated fluid phase:

$$\varepsilon = 1 - \frac{\rho_{\text{dispersion}}}{\rho_{\text{unaerated phase}}}$$

Although the gas hold-up is more commonly used by engineers, an alternative ratio, commonly known as the overrun, is used by food scientists and it is defined as the ratio of the volume of
air or gas included to the volume of the unaerated phase taken. The gas hold-up is based on the dispersion volume and is therefore less than 1, whereas the overrun can be greater than 1. When aeration is undertaken in a batchwise operation, such as the whipping of cream or a cake batter in a domestic mixer, the hold-up increase initially with whipping time, but reaches a maximum and even falls with excess mixing (Fig. 5). The whipping time can therefore be correlated with hold-up and it can be determined in order to achieve a desired value of hold-up. When cake batter is aerated using a whisk – like a domestic whisk – that is partially submerged in the batter, the air from the head space is entrained into the batter and dispersed into it by the mixing action. The level of entrapped bubbles in the batter builds up with time and the hold-up increases. However, this is a dynamic process and, with time, the entrapped bubbles also have the opportunity to coalesce, form bigger bubbles and eventually disengage from the batter. Hence the hold-up variation shown in Fig 6 is observed.

![Graph](image)

**Fig. 6: The variation with time of the hold-up of entrapped bubbles, during the aeration of cake batter using a whisk (Massey, 2002)**

In continuous processes like the one using Mondomix, the batter and the gas phase – which could be air or any other gas – enter the mixing head under pressure, where the gas dissolves in the batter. This dissolution occurs as a result of the well-known Henry’s law in thermodynamics where the solubility of a gas is postulated to be directly proportional to pressure at a given temperature. The amount of gas admitted into the head is also manipulated, so that most of it dissolves and there is negligible loss of the gas simply going through the fluid phase, which can potentially affect the economics of the process. The pressure is released when the batter leaves the mixing head, and the dissolved gas desorbs to form the foam.

Thus, in terms of mechanism of foam formation, there is a significant difference between the way a domestic whisk operates and the way a commercial device like the Mondomix operates. In a simple whisk, the entrained gas is broken into smaller bubbles by the hydrodynamic forces generated by the rotating action of the whisk. The resulting bubble size which remains stably entrapped in the fluid is determined by a balance between the hydrodynamic forces, which tend to break the bubble, and interfacial forces which endeavour to maintain the integrity of the bubble. The ratio of these two forces – also known in engineering literature as the *Critical Weber number* – determines the bubble size (Jimenez-Junca et al 2015). In contrast, when
pressure effects dominate, the gas dissolves under the applied pressure to yield a supersaturated system after pressure release. The supersaturation level acts as the driving force for desorptive mass transfer. Therefore, the resulting bubble sizes will be determined by mass transfer, and not by the hydrodynamics of mixing.

A second major effect of mass transfer driven formation of foams is that the chemical nature of the gas will play a significant role through its thermodynamic solubility in the system. This allows commercial manufacturers of bubble containing foods to manipulate the structure, texture and mouthfeel, simply by varying the gas whilst maintaining the same hydrodynamic feature in the mixing head. Haedelt et al (2007) made bubble containing chocolates by sparging four different gases into a given chocolate mix; the gases were carbon dioxide, nitrogen, argon and nitrous oxide (also known as laughing gas). The same chocolate mix was used in each case, and the hydrodynamic parameters were also the same. After solidification, the product was presented to a trained sensory panel – who found significant differences between the products. The chocolates made with carbon dioxide and nitrous oxide contained significantly higher gas hold-up and the bubble sizes were also greater than the chocolates made using nitrogen and argon. The former gases created a “macro-aerated” product whereas the latter created a “micro-aerated” product. The mouthfeels were also different as a result of the difference in structures. The macro-aerated chocolates were brittle and easily melted in the mouth whereas the micro-aerated chocolates were harder and lasted longer in the mouth. Fig 7 shows the microstructures of the chocolates made using the different gases. The main reason for the formation of macro- and micro-aerated structures may be attributed to gas solubility in liquified chocolate mixes. Carbon dioxide and nitrous oxide gases have much higher solubility than nitrogen and argon. So, the amounts of carbon dioxide and nitrous oxide gases dissolved in a given volume of liquified chocolate were much greater, and consequently, the number and size of bubbles desorbed after pressure release were also greater. It is very important to note that these gases do not remain trapped in the solidified bubble containing chocolate. With time, these gases are replaced by air, and therefore the voids are essentially air-filled. Thus, the gas used mainly served as a structure developing aid. It would make interesting research if chocolates filled with different gases were to be developed! For example, if helium filled chocolates are developed, we could develop a squeaky voice soon after biting into it!

![Fig 7: 2-D structure of bubble containing chocolates made from a) carbon dioxide b) nitrous oxide c) argon and d) nitrogen. The mean gas hold-up values are, respectively, 68, 66, 34 and 39 % and the mean diameter of bubble sections are: 0.51mm, 0.41mm, 0.19mm and 0.13mm, respectively. (Haedelt et al, 2007)
In the case of a head of liquid foam, e.g. cappuccino, the quality, structure, texture and stability of the foam are inherently unstable and highly transient. With time, the gas bubbles coalesce and escape; and the liquid in the foam also drains back into the bulk. Jimenez-Junca et al (2011 and 2015) have extensively investigated the link between the formation of steam injected milk foams and their rheological properties and stabilities. The “product life” of such foams is closely linked to the foam stability.

**Opportunities and Challenges:**

The opportunity to create novel food structures using a zero-calorie food ingredient like air or gases is extremely tempting to explore. In theory, it is possible to take any non-bubble containing conventional recipe and make a lower calorie bubble included version by including gas and bubble stabilising agents. Moreover, the high probability of such products being favourably received by consumers, who tend to associate bubble containing products with celebration and luxury, gives manufacturers considerable market edge. A plausible product development paradigm for such products is presented in Fig 8. A market-led approach is very critical for such product developments, and it is always best to start with the market demand or gap and then work backwards towards process and ingredients. A wide range of structure creating ingredients are available, and the structures of such products are also highly sensitive to ingredients which are used in relatively small proportions in product formulations, e.g. foaming agents. Given how guarded ingredient manufacturers are to reveal formulations of foaming and emulsifying agents, it would be wise for a potential manufacturer of such products to undertake product development in conjunction with an ingredient supplier from the very start, so that formulation and processing conditions are established in a robust manner. In addition to product formulation and the method employed to create the bubble containing structure, there are two other critical challenges. Poor knowledge of the link between microstructure and sensory response makes it particularly difficult to design the product and the process. Published research in this area is also very limited. Commercial organisations may have information relating to their products, but they are reluctant to share such information. Some generic questions can be: do consumers prefer to see uniform sized bubbles? Or is a greater standard deviation in bubble sizes better? Although the questions sound simple, the answers are unfortunately more complex. For example, consumers may prefer to see uniform bubble size in a product like bread or cake, but they may want to see a high spread in bubble sizes in a product like meringue. Further, what level of gas hold-up will result in optimum brittleness for oral processing and enjoyment? Inevitably, bubble containing products are not substantive; so ingredients such as flavours and flavour enhancers may have to be spiked in the recipe. The lack of substantiveness of bubble containing products, again, inevitably leads to lack
to satiety. There is hardly any research available on the satiety of such products. It may seem attractive to lower the calorie content of a bar of chocolate by incorporating bubbles, but if consumers do not feel satisfied with one bubble containing bar and consume more, the very purpose of lowering the calorie can be defeated. Thus, bubble containing products must be formulated in such a way that they are not only acceptable and desirable from a sensory point of view, but also impart consumers with a feeling of being sated. Research into sensory aspects and satiety of bubble containing products promises to be very attractive for the future.

Fig 8: A Paradigm for bubble containing food product development

References:


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