Perspective

Product/Process Integration in Food Manufacture: Engineering Sustained Health

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Introduction

Food processing is a very old industry. Many of the processing operations have been practiced for millennia and many of the problems of the food industry are familiar; for example, Garnsey[1] points out that in classical Rome, most of the population ate cheap meat from roadside stalls or taverns, rather than cooking it themselves. The modern food industry is about 200 years old; Thorne[2] defines the beginnings of the industry to the production of the first-heat sterilization plant in France, developed by Appert in the early 1800s. The industry is now huge; for example, it is 13.6% of the total EU manufacturing sector, with a turnover of €799 billion in 2003. However, the sector is very fragmented with a few multinationals — Unilever, Nestle and Danone for example — competing on the global market with global brands and a large range of products, while smaller enterprises serve local markets and concentrate on regional preferences. In 2001 99% of the companies in the EU F&D sector had less than 250 employees. The business, thus, differs from (for example) the chemical and pharmaceutical sectors, in which a few very large companies dominate the market. Although the major multinationals and retailers can afford to use sophisticated technologies, much of the industry is low-tech. In the U.K., for example, retailers operate sophisticated supply chains that can deliver "cook-chill" products to the market place very rapidly. These products have been cooked and then cooled to a level where microbial growth is minimal;[3] this type of food needs to be moved rapidly from manufacturer to consumer, or the shelf life is unacceptably small, and so this model is not possible in countries the size of the U.S. or in countries with less well developed infrastructures.

The first concern of the food industry is product safety, and it has developed sophisticated design and quality assurance tools to do this. Thermal preservation is still the basis of a large industry. For example, canned food is given a very high thermal process to ensure that it is sterile, although the contents are, as a result, not of very high quality. The death of canning as a process has been predicted for the last 50 years, however, despite such predictions it is still used and studied.[4] Alternative processes that give the same level of safety, but which produce higher quality food have been widely investigated by academics and industry. These include volumetric heating methods, such as microwave,[5] radio frequency[6] and electrical resistance ("ohmic") heating,[7] in which the key processing need is to have thermal uniformity throughout the material.[8] In addition, non-thermal methods, such as high-pressure[9] and pulsed electric fields[10] have been studied extensively; here the heat applied is low, so quality degradation due to heating is minimized. These processes are academically fascinating, but as yet too expensive to be viable for normal food production. The food industry is highly innovative in terms of products, much less so in terms of processes.

Many of the products of the food industry:

- are structurally complex (see Figure 1), and this structure determines the taste, texture and thus eating pleasure,
- involve complex processes in their manufacture, e.g., bread — which involves the creation of microstructure, coupled heat and mass transfer, and the flow and deformation of highly non-Newtonian materials of which the engineering understanding is limited,[11]
- need to be metastable in order to deliver taste and flavor on consumption, for example, the confectionary fats in chocolate are highly polyphasic, with six polymorphs melting within 20°C of one another, and the form that the consumer enjoys is not the thermodynamically stable one.[12]

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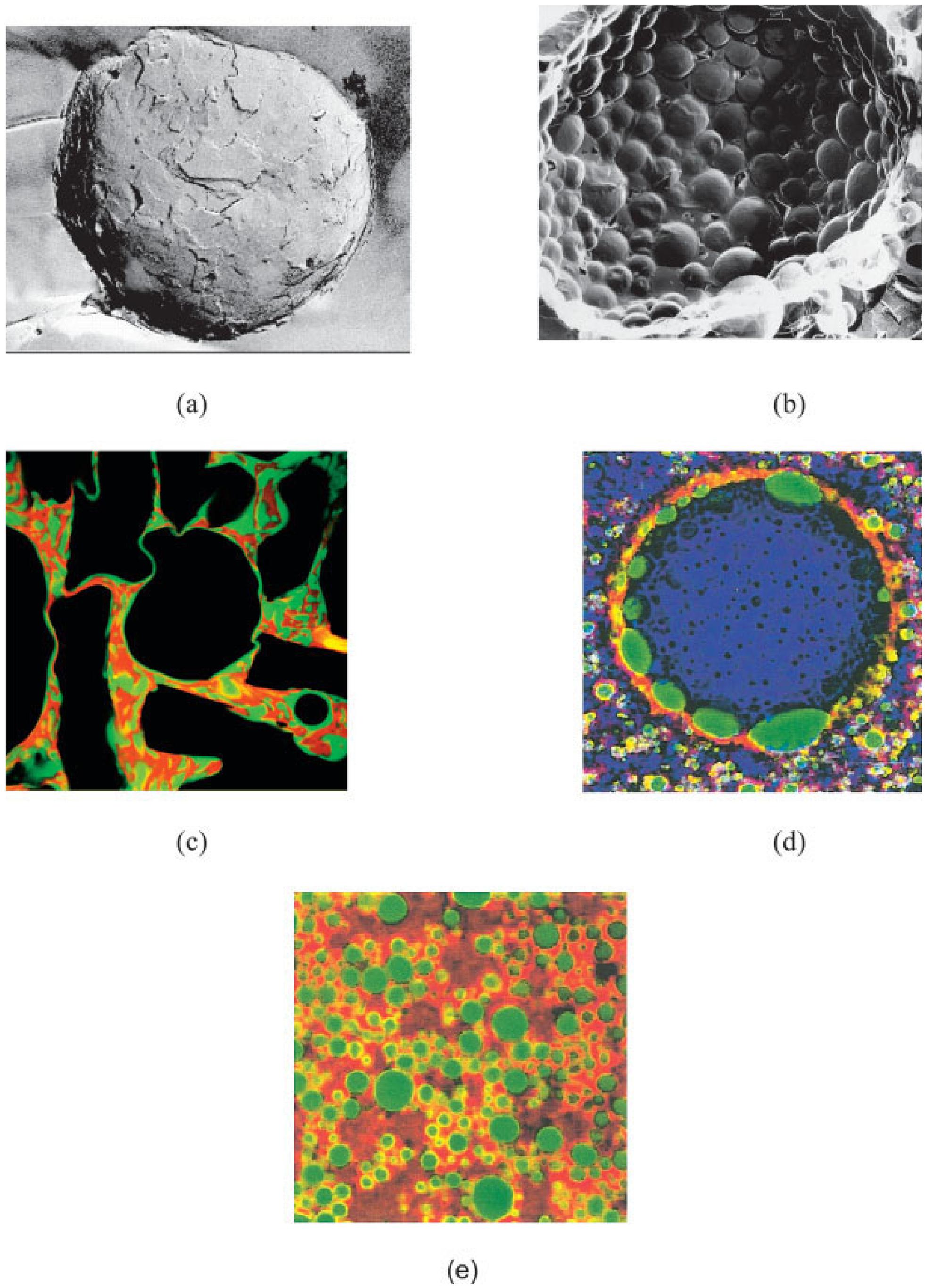

Figure 1. Microstructures of some typical food products: (a) freeze fracture TEM of crystalline fat at the water/oil interface in a fat continuous low fat spread (image width 5 microns); (b) freeze fracture TEM of an air cell in a whipped cream, showing crystalline fat droplets stabilizing the foam structure (image width 20 microns); (c) confocal micrograph of an Ice cream showing phase separation of the biopolymers in the matrix phase (image width 160 microns; green is the milk protein and red is the polysaccharide); (d) Confocal micrograph of an air bubble in ice cream with de-emulsified fat particles (image width 125 microns); and (e) confocal micrograph (image width 80 microns)of low fat mayonnaise showing oil droplets (green) and swollen starch phase (red).

Thus, to make these products efficiently, a combination of understanding of material chemistry and material science is needed, together with an understanding of how the processing which the material receives affects its structure, chemistry and attractiveness.

In the 100 years or so of its existence, the chemical engineering profession has been highly successful in developing the scientific and engineering principles required for manufacturing bulk chemicals. Such products are specified by a chemical composition. However, engineers have been

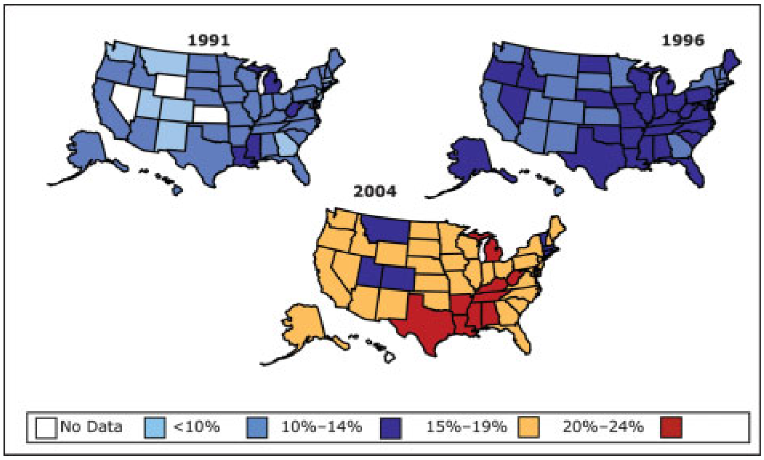

Figure 2. Percentage of the US population (http://www.cdc.gov/nccdphp/dnpa/obesity/trend/maps/), state by state, with a body mass index above 30, regarded as obese, over the past 15 years

less central in the design of structured foods (Figure 1), where the product is specified by a wide range of functions, such as eating and cooking, as well as physical, chemical and microbiological stability throughout the product lifetime. This approach has worked so far, and the food industry has successfully produced a range of products that are attractive and enjoyable to eat. As a result of changes in lifestyle, however, diet is increasingly affecting health (Figure 2), and the incidence of obesity has more than doubled in the U.S. in the past 15 years. The consequences in health terms are very dangerous.

In this article, we consider how engineering understanding of food processing can play a major role in the next stage of development of the food industry, and help reduce the incidence of obesity. We first consider a typical structured food process, that of margarine manufacture, and how understanding of product form and function has been used to reduce fat content. The discussion is then expanded to consider the scope for reducing obesity by designing the next generation of food microstructures.

Designing Structured Foods

The starting point for the design of structured food products is an understanding of the science underpinning the various performance functions. This comes principally from the product microstructure,[13] which in a typical structured food has dispersed phase-length scales of the order of 10 μm composed of liquid or crystallized particulates. These exist within a continuous phase which may be of complex rheology and further structured by polymer or particulate networks.

As an example, let us consider the design and development of spreads. Margarine was invented in the middle of the 18th century as a cheap alternative to butter, to provide a high calorie food product in an age when the diet of the majority of the working class population in Europe was nutritionally poor. It has three main uses:

- As a spread, to provide lubrication and flavor during eating,
- in frying, as a heat-transfer medium and flavor carrier;
- in baking, as a source of fat for texture control.

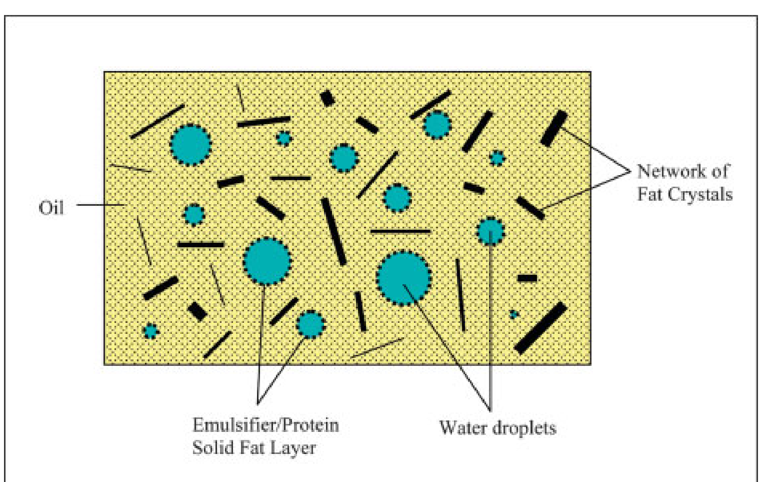

Figure 3. The microstructure of margarine.

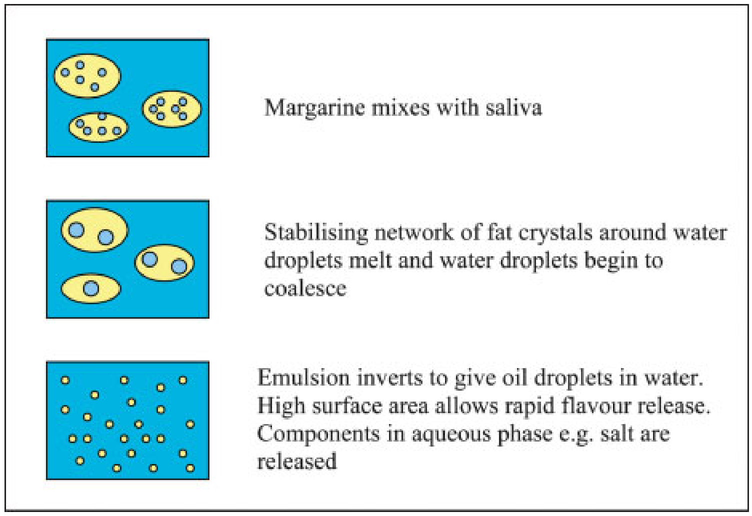

Figure 4. The "in mouth" destabilization of margarine

The structure of margarine, which is a 20% water in oil/fat emulsion, is shown in Figure 3. Absorbed at the water/oil interface is:

- a layer of emulsifier, for size reduction of the drops
- protein which assists in-mouth destabilization
- and crystallized fat (Figure 1a) which stabilizes the droplet.

The continuous phase is oil with a crystallized fat network, which contributes to the rheological and mechanical properties of the material. In addition, the formulation contains colors, flavors and preservatives. There are three main in use functions important to a consumer:

1. *Appearance — controlled by*: water drop-size, crystal size, color
2. *Spreading properties — controlled by:* fat-solids level, crystal size and networking, water-phase volume and drop-size, emulsion stability,
3. *Organoleptic properties — controlled by*: fat-solids level, melting curve, crystal size, water drop-size, emulsion stability, and flavor level.

In designing margarine these functions are characterized and related back to the controlling structural parameters. Appearance, for example, can be related to spectral reflection and absorption properties; spreading to rheological and mechanical properties.

When it comes to in-mouth properties, however, it is necessary to understand the structure breakdown mechanisms involved. This is shown in Figure 4. In the early stages of mastication, the margarine is mixed with saliva, and the fat phase starts to melt. This causes the water drops to coalesce and form an increasingly coarse emulsion leading to inversion and sudden release of water-phase components (e.g., salt), and an increased perception of flavor. To characterize this behavior, simple tests have been developed: for instance, conductivity is measured as a function of temperature; perception in mouth viscosity and melting rates are determined using trained panels. Underlying all these properties is the product formulation in terms of: phase volumes, fat blend formulation, emulsifier/protein levels and microstructure, such as water droplet size,[14] fat crystal size, morphology and networking.

The process for manufacturing margarine has four objectives:

1. Pasteurization to increase product shelf life,
2. production of a controlled mean-water droplet size,
3. production of a minimum fat crystal size,
4. control of the fat crystal network.

To minimize fat crystal-size rapid cooling is applied in high-surface to volume scraped surface heat exchangers, so that nucleation dominates over growth. Fast cooling, however, forces the fat into a metastable α polymorphic form that trans-

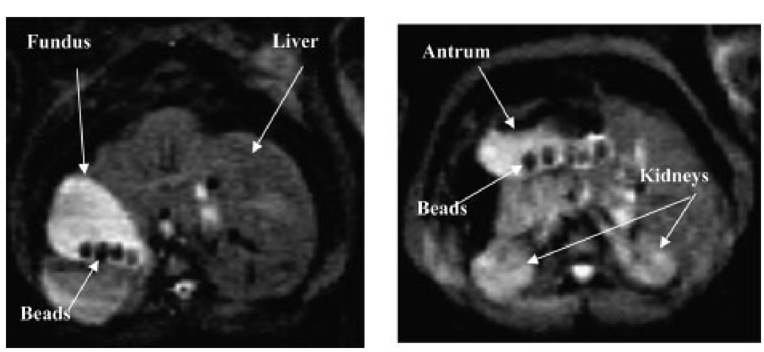

Figure 5. MRI visualization of agar gel beads in the human stomach,[27] (a) intact beads in the fundus, and (b) intact beads in the antrum, used with permission of The American Physiological Society.

forms over a period of a few minutes into the more stable β' polymorphic form.[15] In the absence of shear this would lead to extensive networking and very hard products. The material is, therefore, "worked" in a pin stirrer, which provides residence time for the polymorphic transformation, and applies mechanical energy to the system to break up the crystal network. The sequence of scrapped surface heat exchanger followed by pin stirrer is repeated one or more times in order to develop an appropriate degree of crystal network in the desired polymorphic form, before packing and distribution at 5°C, to minimize kinetic effects on structure, such as Ostwald ripening and microbiological growth. The first scraped surface unit also subdivides the emulsion droplets to produce a fine emulsion with typically 5 μm water droplets.

From its invention until about 30 years ago, margarine changed little as a product. However, increasing awareness of the effects of high dietary fat levels and saturated fats on cardiovascular disease (CVD),[16] have provided the opportunity for, and led, to a revolution in two directions:

1. Reduction of saturated fat level (SAFA),
2. reduction of absolute fat level.

The first of these was further amplified as evidence showed that high polyunsaturated fat levels (PUFA) in diet could aid the prevention of CVD.[16] From the product and process design perspective, while the need to reduce SAFA and increase PUFA levels provided the opportunity to design new "soft spreads" it also set challenges in controlling crystal networks with minimum solids levels and control of crystallization at the water oil interface[17] to stabilize the water phase with fewer solid particles.

The need to reduce fat level set even greater challenges in controlling emulsion structure and stability as levels were reduced to 60% then 40% and lower. New processing and structuring technologies were introduced.[18] It was found for fat continuous low fat spreads, for example, that inversion processing of a water continuous premixes led to smaller water droplet sizes and better products. Structuring of the water phase with biopolymers was required to control stability and improve organoleptic performance. Ultimately, this led to the development of phase separating biopolymer systems which could mimic the rheological behavior[19] of water in oil/fat emulsions allowing the development of 0% fat products.[20] Most recently, spreads have been used as the delivery vehicle for fat soluble actives which can reduce blood LDL cholesterol levels.

This story is not unique and similar examples can be found for:

- Sauces and dressings where the structure of the oil in water emulsion (Figure 1e) controls the performance of the product and low fat versions are designed to have hydrated starch grains to mimic oil droplets.
- Whipped cream and ice cream, which depend on crystalline fat droplets at air bubble surfaces to stabilize the foam (Figure 1b and d) and to give the required oral properties. In both these products the water phase contains biopolymers that additional have their own microstructure (Figure 1c).

Current status of structured foods product and process design

Currently, the development of new structured foods is still separated into product development and process scale-up phases. Product development is carried out at the laboratory/mini-process unit scale using a combination of qualitative models of structure/performance behavior and experience. These allow the development of first prototypes that are characterized, analyzed, and refined using the types of method described earlier for margarine. Some of these will relate quantitative measures of structure to performance; many infer structure performance relationships from empirical measures of a bulk property. Final evaluation and acceptance is by consumer testing.

Frequently in the product development phase standard equipment that is poorly characterized or controlled from a processing perspective is used. Furthermore, preservation regimes very different from those required in final manufacturing are often employed.

As noted earlier, process innovation in the food industry has also been comparatively slow compared to others. For a particular product type, a limited range of unit operations have been employed for some considerable time, and the same process line is used to make a range of different product structures; as is the case in spreads processing. A particular design objective and its processing solution, such as long shelf life via UHT processing, can come to dominate the product design, so that it is applied broadly across product types and leads to large compromises in product structure and performance, and to problems in the scale-up and commercialzation of new products.

Health Driver

So what is the next big driver for the food industry?

As mentioned in the introduction the number of overweight and obese individuals[21] is increasing rapidly. Governments are faced with a number of ways forward:

- A pharmaceutical solution: use drugs to treat the disease once developed. This approach is prohibitively costly.
- Tell people what to eat and to instruct them to lose weight. In this scenario governments will tax unhealthy foods and even remove medical care for people who are obese or even overweight. However, this is a parallel to the government response to smoking that has not worked and a significant proportion of the population continue to smoke unabated.
- Blame the food industry for making "unhealthy" foods that are too tasty and that cause people to overindulge. In this scenario governments will tell the food manufacturer to redesign their products and legislate against unhealthy products.

It is our hypothesis that the only way forward for the food manufacturer will be to encourage a change in lifestyle and to develop the next generation of foods, designed to be convenient, cheap, nutritionally balanced and enjoyable to eat. These foods will be structured in such a way as to control the rate of release of macronutrients and slow the rate of the stomach emptying so limiting the amount of food that people consume.

Human Digestive Machine

All foods pass through a common unit operation, the GI tract, yet it is the least studied and least understood of all of the food processes. In order to design the foods of the future, chemical engineers will need to understand what happens inside people in the same way as any other process.

The mouth, as discussed earlier, is a complex environment in which the food is broken down by chewing action, it is mixed with saliva that contains enzymes and it undergoes a temperature change as heat flow occurs.[22] The foods are then processed to a stage were a bolus can be formed and swallowed. As these processes are occurring, molecules are released into the headspace and delivered to the nasal cavity.[23]

A number of investigators are actively researching product microstructure design for in mouth behavior and delivery of molecular species, such as flavors, tastes,[24] aftertaste[25,26] and physical sensations, such as fatty feeling or mouth coating.

The next stage is to consider how the food behaves in the stomach (Figure 5). MRI studies[27,28] have shown that the stomach behaves as a poorly mixed system in which the walls oscillate a small amount causing some surface mixing and erosion. At the same time, acids and enzymes are added to help breakdown the food into materials that can be absorbed into the blood stream. The time taken for complete digestion depends on the original food structure with liquids digested more rapidly than semisolids or cellular structures.

This area of research is hampered by the available techniques that are either intrusive or too slow or too low a resolution. In the near future there will be measurement techniques[29] including rapid NMR imaging methods that will overcome these limitations. This will allow chemical engineers to build mathematical models of the stomach and design products for the processes occurring.

The small and large intestines are the most difficult part of the process to make engineering measurements. As such, little is known about the processes that occur from an engineering perspective. This is likely to change over the next few years as MRI is just starting to be capable of measuring the processes,[32] and the first basic models[30,31] are starting to appear.

Food Structuring Opportunity

The opportunities for food manufacturing can conveniently be divided into:

- Controlled rate of release of macronutrients.
- The ability to have self-assembly of structures inside people.
- Encapsulation and targeted release of functional ingredients.
- The ability to get more functionality from macronutrients.

Release of macronutrients

There are potentially three ways to design microstructures to control delivery of fat and modulate people's food consumption at lower fat levels:

1. Emulsions that are unstable in an environment similar to the stomach coalesce and cream.[33] This leads to the fat forming a layer on the top of the stomach where it interacts with receptors and sends signals to the brain about the state of satiety. There is, therefore, the potential to design emulsions to break inside the stomach within the timescale of eating the meal to signal the feeling of fullness/over indulgence, and, thus, limit the amount of food consumed at the meal sitting. The technical problem that needs to be overcome is to combine storage stability and in use performance, with instability in the stomach.

2. Spiller et al.[34] has suggested that, if fat passes from the stomach into the ileum without being digested, then the body responds by sending signals to the brain slowing the rate of stomach emptying and slowing digestion, the so-called ileal break effect. Emulsions/mixed emulsions will be designed in the future to give all the eating pleasures and performance of present products but with this new functionality.

3. The physical state of fat[35] changes the rate of digestion, with solid fat crystals digested more slowly than liquid fats as a consequence of the slower rate of chemical attack. However, the use of long chain saturated fatty acids that are nutritionally unhealthy will need to be limited, and any solid particles will need to be hidden during consumption to avoid sandy/gritty sensations. A potential way around these problems will be to develop Pickering[36] emulsions with very small droplets having solid crystal shells at body temperatures and liquid oil cores (unsaturated/nutritionally good oils).

As convenient foods and the tendency to snack has become the normal behavior, people are eating softer more liquid like products. A consequence of this is that the proportion of digestible carbohydrate has increased at the expense of fiber. In addition, the digestible carbohydrates are readily available immediately and absorbed much more quickly.[37,38] This results in high glucose levels in the blood shortly after the meal, which is then stored quickly inside the body, leading to a rapid onset of hunger and a desire to eat again. This pattern of blood glucose levels has been linked with an increased risk of insulin intolerance and type II diabetes.[39]

The food industry needs to develop soft/liquid foods that deliver glucose over an extended period of time. Potentially this can be achieved, for instance, by encapsulating carbohydrates and starch inside nondigestible hydrocolloids, reducing the rate of amylase attack. A challenge is how to achieve this "slow burn' while retaining all the other product attributes.

Self-assembling structures

Liquid products can be made to self-structure inside the GI tract[40] by choosing hydrocolloids that are acid sensitive, e.g., alginate (extracted from kelp) and gel within microseconds below pH 2.5. Thus, as the liquid alginate solution reaches the stomach, the acidity causes spontaneous gelation. With careful selection of the alginate, it is possible to gel the whole stomach content, slowing both digestive processes and stomach emptying. Maintaining stability of the formulation in real foods is an ongoing challenge. Such problems will be overcome and self-structuring products will reach the market that deliver varying degrees of mechanical rigidity from a wide range of food products — liquids, semi solids to solid foods. Potentially this will have major impact on the obesity problem.

Encapsulation and targeted release

Functional peptides can bind to receptors in the GI tract and influence the feeling of satiety, impact on stress levels and even affect our mood.[41] However, most of these materials are unpleasant to eat and are often chemically unstable in storage or in use. An opportunity for the food manufacturer is to encapsulate these materials in ways which allow release at the desired place and rate in the GI tract. In addition, by designing the product microstructure to positively interact with bio-surfaces inside people we will have biologically targeted products.

People find it difficult to follow the current recommendation to eat between five and ten portions of fruit and vegetables a day in order to get the right balance of micronutrients and the required daily intake of complex carbohydrates[42] (dietary fiber). In addition, the cellular nature of fruit and vegetables is important in order to fill the stomach and be slowly digested. In the future microstructural design will allow convenient good tasting products that deliver the required high levels of fiber, bulk and micronutrients to be developed.

Reduction of energy dense ingredients; fat and sugar

Clearly, the replacement of fat in products is critical to fight obesity, and there is a real need among food manufactures to reduce the amount of fat that is invisible to the consumer.

Fat replacement was an area of interest a few years ago,[43] and a number of products appeared in the market. Some of these are still on sale, e.g., low-fat spreads, low-fat biscuits and cakes, etc. However, many of the products launched did not survive due to poor taste and texture. In a number of these products high levels of sugars were used to maintain succulent textures, thus, resulting in only marginal calorific advantages.

A systems approach based on understanding the dependence of performance on the physical chemistry and structuring of fat is required to solve this problem. To be successful, products must be developed that deliver flavor at the desired rate. If flavors are delivered in the wrong way, then an imbalance is perceived resulting in hollow or unpleasant flavors. Products need to coat the surfaces of the oral cavity and the throat resulting in the physical feeling of fat and delivering pleasant aftertastes.[25,26] Low-fat emulsions with as little as 5% fat can give the feeling of fat as they break in the thin film between the hard palate and the tongue.[26] The sensation of melting is potentially the most difficult to replace.

It is clear that to reduce fat significantly the food manufacturers will need to extend the functionality of any fat used in the product for instance by building smart structures, such as stable duplex emulsions with a thin coat of fat around a structured water phase with an inner core of fat acting as a flavor sink.

The replacement of sugar with artificial sweeteners has had a significant effect on the intake of calories. However, sweeteners taste artificial and are frequently reported as having health issues.[44] Potentially, an alternative route will be to increase the efficiency of sugars in the product by designing microstructures to interact with the receptors for longer, and to deliver a larger proportion of the sugar present to the receptor. This should give the perception of sweetness from a low sugar product. The need is to make binding specific to the soft surfaces of the mouth to avoid binding to teeth for long periods of time resulting in increased tooth decay.

Sugar is not only used to impart sweet tastes. It often has a structural use as well, for instance, the retention of water in cakes, biscuits, etc., to impart succulence on chewing, or for controlling ice formation and ice content in ice cream and frozen desserts, and for controlling the material properties of composite products, such as chocolate and sorbets. There is potential to replace at least some of the sugar in these applications.

The Way Forward

Structure/property relationships

Ottino has made the point[45] that a key development in chemical engineering in the period 1960 to 1980 was "*the adoption and mastering of mathematical tools that opened new horizons and helped define the profession*". Presently, new food product development uses largely qualitative models of structure-function relationships, necessitating cycles of prototyping and testing to develop the final product. A key requirement to move forward will be the development of better understanding of the mechanisms underlying the functional behavior of a given food structure, and the ability to quantify this using mathematical modeling. Some progress has already been made.[46] If, however, we are to exploit the opportunities of foods with health advantages from their behavior in the human digestive system, it will be necessary better to understand and predict the digestion and subsequent metabolism of structured functional foods. This is an area where the skills of the chemical engineer can be used to advantage, but now in the context of the processes and unit operations of the "human machine". Chemical engineers themselves will need to take the lead in working with physical chemistry and biosciences to put in place the underlying mechanistic models and develop the mathematical tools to deal with these complex systems.[47]

Integrated product and process design for control of product structure

The structuring process is integral to the design of a structured product. Hill[48] rightly argues that product and process development for structured consumer products needs to be carried out concurrently. This is not only from the perspective of facilitating scale-up, but also to use the opportunity of developing novel structures through innovative processing. An example would be the adoption of extrusion processing for ice cream. This technology allows ice cream to be extruded at low-temperature, −12°C compared to −5°C for the traditional process using scraped surface heat exchangers. Extruder processing reduces the time required to take the product to normal storage temperature of −25°C and, therefore, the impact of ripening processes on ice crystal-size distribution. Additionally, however, the process also has significant effects on the structuring of the air phase resulting in smoother creamier products for a given composition. Here, the process gives a better product.

To achieve integrated product and process design, prototyping equipment in which the structuring conditions are well defined and controlled need to be used. Similarly, the ability to predict structure-process relationships needs to be developed from its current level. This should be core to the chemical engineering skill base, but once again new approaches in mathematical modeling may be necessary to deal with the complex mechanisms involved.

New paradigms for processing and manufacturing

The manufacture of structured foods is still mainly based around a limited number of traditional unit operations in centralized factories taking advantage of economies of scale. These unit operations allow limited control over product structure. To produce some of the structures that will be needed for functional behavior in the human digestive system, new unit operations will be required. It will be necessary to rethink the production of structured particulates from the bulk processing of material to operations which structure at the individual particle level. An extreme example would be the application of microfluidics to structured material design.[49] Encapsulation technology based on the breakup of concentric jets from fine nozzles is already well developed, but has yet not found application in the foods industry. In addition to achieving greater control over product microstructure such technologies move scale-up from the duplication of process conditions in larger volumes to scale-up by parallelization. While this might at first seem to simplify scale-up, it will bring new challenges in distributing fluids uniformly to large assemblies of small channels.

The "one size fits all" solution will not necessarily be applicable for foods providing health benefits. Manufacturing will need to be able to accommodate some level of product variation for particular groups or in the extreme case make individualised products. Solutions to this problem will vary from late customization on production lines in centralized factories to new approaches to the supply chain. Centralized facilities may be used to make a "base" material that is finished at distributed points, such as warehouses, based on orders received. Individualized products may be manufactured at point of sale. Recently, an industrial perspective for the manufacture of individualized foods and healthy foods has been published.[50]

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