

GOOD FOOD REQUIRES PROCESS ENGINEERING?!

Simultaneous product and process development

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There is a seeming contradiction between the cry-out of the consumer for fresher, less processed and more natural food, and the simultaneous demand for higher safety, better nutritional balance, and instant, convenient availability of food. The negative image of processing might be explained by the dissatisfaction of the consumer with many of the products, prepared by the conventional processes to preserve foods that are normally eaten freshly prepared.

Process engineers have traditionally shied away from modelling and optimising processes on parameters like taste, crispiness, and spreadability. Now, understanding of the relation between sensory perception and product structure, as well as modelling of all effects influencing this microstructure in an integrated environment is starting to enable systematic process and product design also for structured foods. This is illustrated with two case studies.

1. Introduction

Modern consumers of food have a strange attitude towards food processing: on one side they increasingly demand fresh, natural food where no one has 'tampered' with. On the other side they want all products to be available to them all year round, wherever they are and whenever they want it and they want it right away, not after three hours of cooking. While the western population is increasingly getting overweight or obese, they demand good, but low calorie food. While the words 'processing' and 'additives' are becoming taboo, it is not realised that the most popular foods wouldn't even exist without being processed: cheese, beer, wine, bread, jam, butter, oil, yoghurt, soy sauce, sauerkraut, ham, salami, and, for the Dutch: rookworst, are all successful results of attempts of our ancestors to preserve the harvest they obtained with so much effort. In fact, food processing is probably the oldest form of process industry that exists. Still today, on a global scale, a worrying part of the food is lost after harvesting due to spoilage.



Fig 1: Food processing is one of the oldest existing processing industries: left- an oil mill at around 1600, right- a similar oil mill in the 1960's

On the other side, the 'real' process engineers have always shied away from food processing, talking disdainfully about food processing factories as enlarged kitchens, looking proudly at their distillation towers and reactors. One could wonder whether this is actually because they couldn't handle the complexity of dealing with systematic design of processes for food products. While in many chemical and pharmaceutical processes one can characterise the end-product and process streams by parameters like pressure, temperature, composition and particle size distribution, it seems virtually impossible to tune a heat exchanger or a homogeniser to optimise parameters like: better taste, more crispy, creamy or 'rich'. Yet process design is just as key for the foods industry as a cook is to a meal: a bad cook can ruin a meal, even when he uses good ingredients, while a good cook can even

make something out of bad ingredients. A poorly designed food process ruins the best ingredients, while a well designed process still can make something from poor ingredients.

So the food processing industry is faced with consumers that say they don't like processed foods, but increasingly demands processing for better quality, nutritional value, safety and health and with process engineers that are incapable of handling the complex nature of foods in a systematic way. Yet the quality of the food depends completely on the way it has been made. In this presentation I will illustrate how nowadays increasingly the needs of modern, demanding consumers, can be met through a systematic, hand-in hand design of process and product.

2. It is all about understanding product microstructure

A mixture of starch, protein, salt and water doesn't characterise bread, even though bread is a mixture of starch, protein, salt and water. Actually the properties of a bread are only to a small extent determined by its actual composition and mostly by its structure: the size of the air cells in it, the structure of the crust, the elasticity of the air cell walls etc make bread either dry and crumbly, or soft with a crispy side.

In general, most of the consumer relevant properties of food products are related to their structure, rather than to their composition: the gloss of a margarine for example can be derived from the size of the structural elements on its surface: fat crystals and water droplets, a creamy aftertaste to the presence of small fat globules on the tongue etc.

Hence in systematically designing a food product we must ideally be able to:

- First relate consumer liking (hmm..this product tastes good!) to his sensory perception of the product (it has such a creamy aftertaste).
- Secondly, we need to relate this subjective sensory perception to objective characteristics of the product microstructure (the size of air bubbles in a sauce for instance).
- Thirdly, we can then use these micro-structural characteristics as the target for determination of the ingredients and processes needed to build that microstructure. (with phase viscosities a and b and surface tensions c , we need a flow field like x , in order to be able to produce droplets of size y)

The first two items are the subject of an emerging science called psychophysics, while the third can be expressed in robust relations dictated by the laws of physics and chemistry. However, without some form of understanding of the first two steps, the third step becomes meaningless. Though in principle possible, even the third step, systematically designing ingredients and processes for building a desired food product microstructure is easier said than done, in view of the complex, poorly characterised systems foods are. I will illustrate this with two examples: fat free margarine, and high quality chunky soup.

3. Integrated design of a fat free margarine.

Margarine and halvarine are emulsions of 20-40% water or milk into liquid oil, stabilised by a network of fat crystals. See fig 2. The properties of margarine (melting, spreading, and taste) are dominated

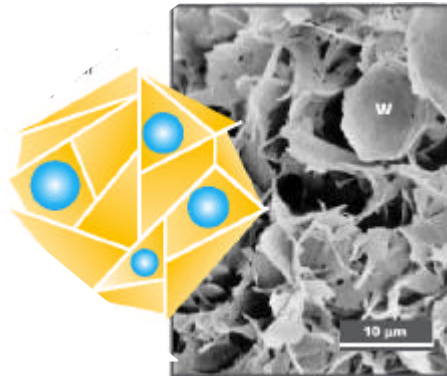


Fig 2: structure of a margarine: left an electron-microscopic image, right a simplified model. The EM picture clearly shows the fat crystals and the W indicates the fat crystal shell around a water droplet. The black pores were filled with liquid oil. (picture from I. Heertje, Unilever Research)

by the structure of the product

Overweight and obesity are an ever increasing problem in the western society, with currently in some countries almost 50% of the male population over 40 being overweight. As obesity is a major risk factor for cardiovascular diseases and diabetes, there is a need for good quality reduced calorie foods. In this context a fat free margarine might be useful.

Assuming the properties of the product remain unchanged if we keep the structure unchanged, we can set out for a design of an almost fat free product:

- ❑ The liquid oil (93% of the fat) needs to be replaced by a calorie free liquid substitute: we propose to take slightly thickened water.
- ❑ Replacing oil by water leads to two issues:
 - how to get the water into the hydrophobic pores of the fat crystal network,
 - and how to still maintain the product's character of an emulsion: i.e. how to emulsify water in water.

An answer to first question can be found in the self-assembling liquid crystalline structures of amphiphilic molecules and their complex phase behaviour. Depending on their geometry, amphiphilic molecules in water form micelles or reversed micelles or lamellar bi-layers. These can self-assemble to hexagonal, inverted hexagonal and cubic phases, depending on composition, temperature and process history.

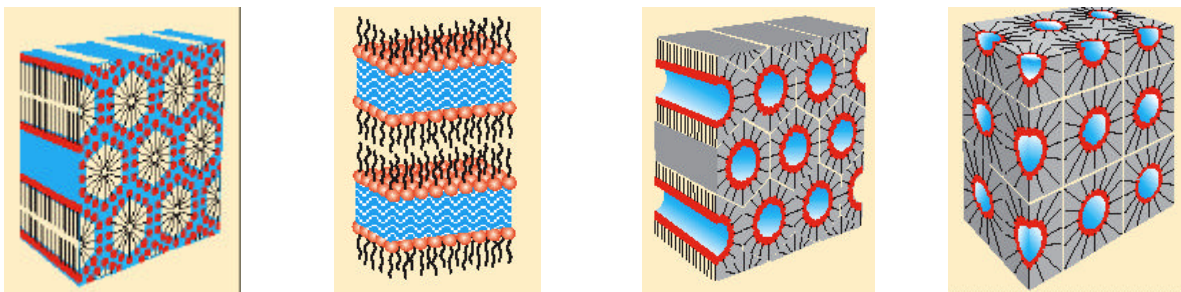


Fig 3: Mesomorphic phase behaviour of amphiphilic molecules: from left to right: the hexagonal, the lamellar, the inverted hexagonal and the cubic phase. Blue is water, black are a-polar (fatty acid) chains, and red are the polar (glycerol) head groups. (from Zeelenberg, 1995)

All these structures hold water in between 'fatty areas'. The lamellar phase holds most water, especially with the use of ionic co-surfactants they can hold >95% water. The lamellar phase crystallises into an alpha-gel when cooled below the so-called Kraft-temperature. This alpha-gel is unstable and transforms into a crystalline beta-coagel, a network of fatty crystals, with the polar head group oriented towards the surface, such that the pores are now hydrophilic, rather than hydrophobic.

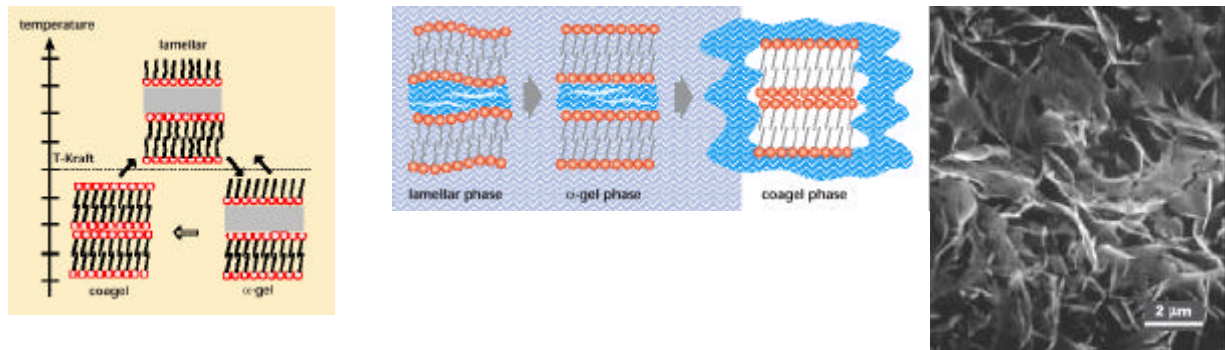


Fig 4: Transformation of the lamellar phase into an alpha-gel below T_{Kraft} , and subsequent re-crystallisation into a beta-crystalline network with expulsion of water into the crystal network pores. EM picture of the beta-coagel phase (from Heertje, Unilever)

This is the desired water-holding fat crystal network, and indeed the coagel phase feels, spreads and looks in all aspects like crystallised fat.

The second question, emulsifying water in water, can be addressed using a phenomenon from polymer chemistry, of de-mixing of mixtures of polymers in presence of a solvent, which can be described with the well known Flory-Huggins theory. Not surprising we have found that this also holds for mixtures of biopolymers of sufficiently different chemical nature: e.g. a solution of protein and starch de-mixes into a protein rich phase and a starch rich phase. The behaviour can be sufficiently accurately described for process modelling purposes using Flory-Huggins, provided the interaction parameters are known (A.H. Clarke, Unilever, 1998). Though never determined for food systems, we found that the normal group contribution methods, like UNIFAC, can be used. Hence, a protein/starch mixture could give us a water in water emulsion, provided we choose a composition that de-mixes and we manage to emulsify one phase into the other.

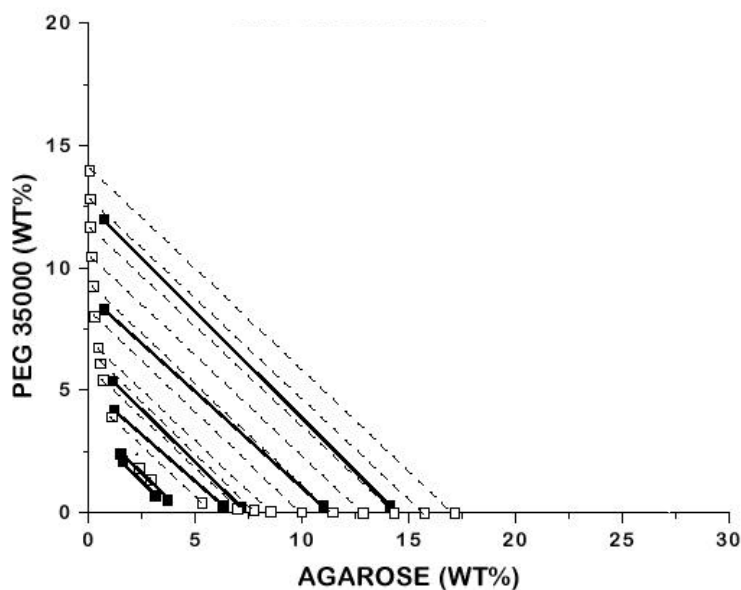


Fig 5: Fitting of tie lines of polyethylene glycol (PEG), agarose and water ternary mixtures using Flory-Huggins. (From A.H. Clarke, Unilever, 1998)

However, mixing amphiphilic molecules that form lamellar phases, like simple monoglycerides and lecithins (both natural components), and protein, starch and water together, heating to pasteurise, cook the starch and dissolve the emulsifier followed by cooling and stirring, (i.e. the standard margarine process) is not going to result in the correct structure, of course:

- At pasteurisation temperatures the emulsifier and water form stable cubic or hexagonal phases, rather than a lamellar phase.
- When a lamellar phase is brought in contact with hydrated starch, starch and emulsifier form a stable complex that precipitates,
- The presence of protein prevents the formation of the alpha-gel out of the lamellar phase,
- There is no control which of the two water phases will become the continuous one.
- When the beta-coagel is sheared, it loses its water holding capacity dramatically.

From these constraints, a likely process to build the desired structure can be synthesised:

- the lamellar phase must be prepared separately, and be pasteurised at very low temperatures by optimising pH and holding time.
- That requires a very concentrated disperse phase to be prepared separately for later mixing with the emulsifier phase. However, in that system the phase with the largest phase volume will tend to become the continuous phase. By choosing a protein that gels faster than starch as the disperse phase (gelatine), and cooling the mixture to below gelation temperature, the system will be forced to a state with the slowest gelling phase as the continuous one, regardless of phase volume.
- Starch and lamellar phase cannot be mixed, but the complex doesn't form when the emulsifier has crystallised, hence alpha-gel and beta coagel can be mixed with starch.
- The coagel needs to form in rest, after filling of the product; hence the starch continuous concentrated emulsion needs to be mixed into the alpha phase.

The final process consists of two main streams, one where the lamellar phase is prepared, carefully pasteurised and cooled below T_{Kraft} , such that the alpha-gel forms and one where a concentrated dispersion of protein gel droplets is prepared in a starch continuous phase by cooling and shearing till the protein has gelled, followed by a well designed mixing step, with the alpha-gel, before any transformation to beta has taken place.

The final product microstructure is identical to margarine. And indeed, when tested with consumers, they cannot distinguish a difference in appearance, spreadability, kneadability, and mouthfeel, even though the composition of the product is entirely different and consists for 93% out of water in stead of 80% fat.

[One thing was omitted from these considerations: the oil that has been replaced is also a carrier of fat-soluble flavour components. There are no components in the new product where fat-soluble flavours can dissolve, and as a consequence, consumers do notice clearly that the product tastes completely different]

4. Good quality chunky soup.

Particulate food systems form a large part of normal meals; e.g. meat in sauce, stews, pasta sauces, curries, and hearty meal soups.

Traditionally the industrial preparation of these products does indeed look like an enlarged kitchen: the soups and sauces are cooked in 200-1000 l. kettles, transferred to a hopper and filled. After filling the products are sterilised stagnant in an autoclave.

Though the process looks exactly like that in the kitchen, the result is quite different: indirectly heated big kettles take much longer to heat than a pan and the hot holding time is much longer than at home. (If the family members arrive at the correct time for dinner, everyone knows how a meal tastes that has been kept warm for half an hour) And if that is not enough, a final sterilisation at 120 C for sometimes several hours does the rest.

One might speculate that the quality of these foods has given food processing its bad reputation with the consumers. Processed has become synonymous with poor quality, vitamin loss etc. When the consumer asks for unprocessed, artisanal foods in its quest for good quality and fresh taste, she asks in fact for adequately prepared good tasting foods.



Not surprisingly, really understanding the processing of particulate foods is very difficult. It is a careful balance between product safety and product quality. In order to do that one needs to be able to integrate a multitude of effects into a general model, able to deal with these effects in any process

line, of any geometry for non Newtonian streams with particles of any size, load and shape, while taking into account residence time distributions:

- For safety, the bacterial thermal death kinetics needs to be described. Not through the standard models in literature, that give a bulk death rate as function of temperature, but a model that takes account of the local environmental conditions on death kinetics: pH, local temperature, temperature history, water activity etc.
- Enzyme activity and deactivation kinetics must be described to track the fate and the activity of enzymes like amylases (influences structure) and proteases (influences taste)
- Chemical reaction kinetics need to be modelled: browning, loss of vitamins as function of oxygen and temperature, flavour formation reactions (e.g. Maillard reactions)
- Hydration and gelling kinetics of bio-polymers must be known
- The phase behaviour of fats, emulsifiers and biopolymer systems must be known.
- Particle softening upon cooking must be modelled, and as a consequence, also particle attrition in shear fields i.e. decrease in particle diameter and integrity upon increasing softness and increasing shear.
- Also for safety, fouling and cleaning kinetics of the process equipment must be described
- As well as pressure build-up in line, and thawing and freezing kinetics of the particles.

For each of these effects, we need to have reliable estimates of the material properties needed for describing it. Generally for foods, parameters like heat conductivity etc are not known.

Using state –of-the –art mathematical modelling tools developed within Unilever Research in collaboration with other expert centres, we are now capable of detailed flow simulations of particulate flows in non Newtonian fluids. Integrated with models for each of the effects above, it provides an unprecedented insight into the phenomena taking place during the thermal processing of products like chunky vegetable soups. An example of such flow simulation is given in fig 7.

From the simulations, we can follow in time the evolution of the concentration of bacteria in the foods, which is really what we want to be able to control them. It is immediately clear that the largest concentrations remain inside the particles, and that particles close together heat slower than the free flowing ones. In addition we can now start to balance quality and safety. For instance, if the main quality defect would be 'mushy, overcooked vegetable particles' we can have a look at particle integrity as a function of the process applied and systematically optimise particle integrity, while watching safety

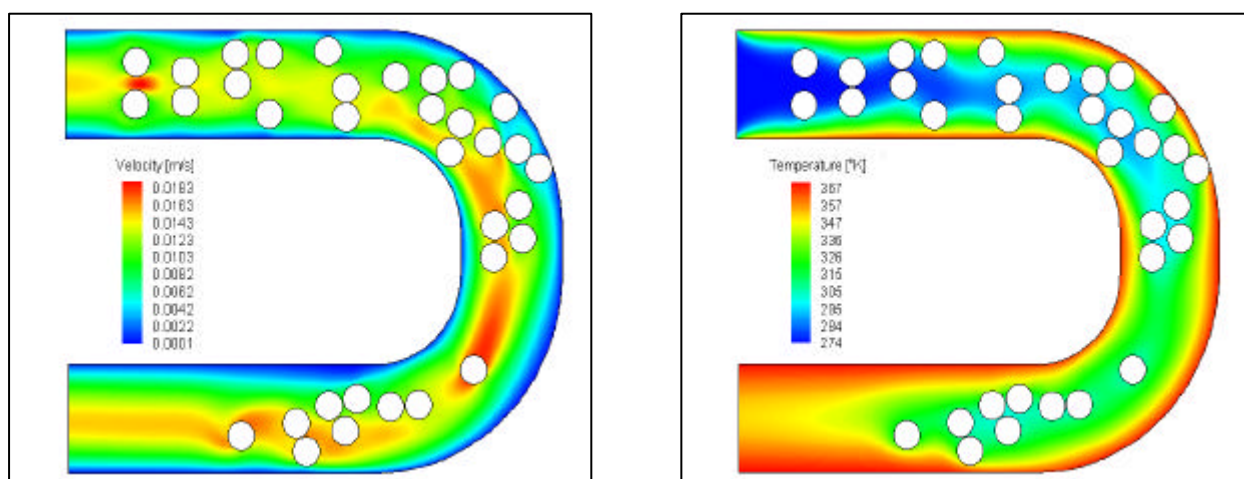


Fig 7: CFD simulation of the flow of a model particulate containing soup through a tubular heat exchanger. Velocity and temperature profiles of the fluid are indicated (Jongen, Unilever, 2001)

A model for particle integrity can be developed, describing loss of particle diameter as a function of particle consistency (which in turn is a function of particle nature and thermal history of the particle), strain rate (as a function of location in the process), and attrition rate (which is a function of temperature and location in the process). A simple experimental device can be used to determine the key raw material properties.

Subsequently, one can simultaneously assess quality and safety, as is illustrated in fig 8. And finally, from this an optimised process design follows, leading to much higher throughput and much better quality as in the original trial and error process, while retaining safety. (Fig 9)

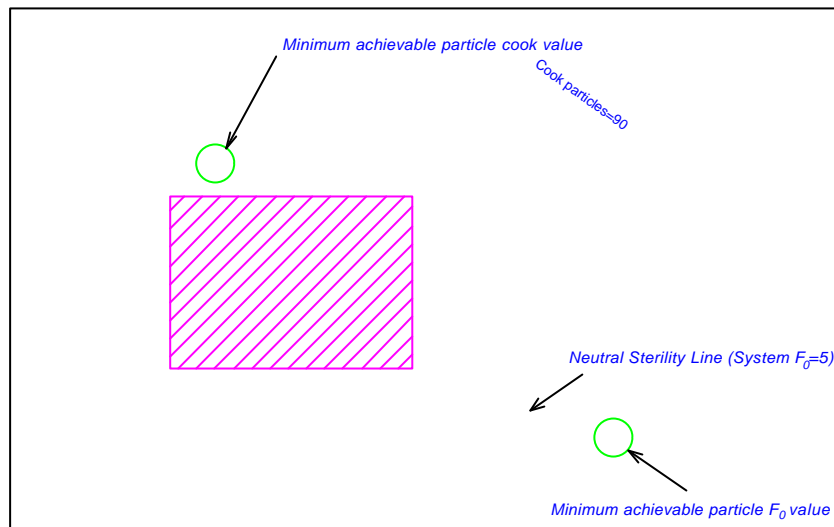


Fig 8: Concurrent process safety, quality and feasibility assessment using integrated process modelling (Jongen, 2001)

Integrated modelling can be used both for process improvement, as well as reduction of product development. It requires that the various sub-models, which come from very different disciplines as microbiology, flavour science, physical chemistry and enzymology are all developed in a modelling environment that allows use, re-use, adaptation and coupling of the all these different model components. While one single sub-model is hardly of use in a food business context, rigorous integration into a user-friendly interface allows the simultaneous design of optimal products and processes. It indeed creates the ability to link sensory perception finally to process design.

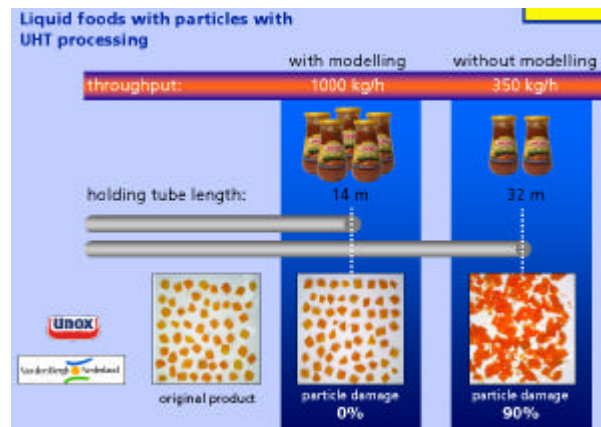


Fig 9: Simultaneous optimisation of process throughput and product quality, whilst retaining safety in a product, containing carrot particles

5. Conclusion

There is a seeming contradiction between the cry-out of the consumer for fresher, less processed and more natural food, and the simultaneous demand for higher safety, better nutritional balance, and instant, convenient availability of food. This negative image of processing might be explained by the dissatisfaction of the consumer with many of the products, prepared by the conventional processes to preserve foods that are normally eaten freshly prepared.

Process engineers have traditionally shied away from modelling and optimising processes on parameters like taste, crispiness, and spreadability. Now, understanding of the relation between sensory perception and product structure, as well as modelling of all effects influencing this microstructure into an integrated environment is starting to enable systematic, integrated process and product design.

The increasing demands of consumers for safety, health and environmental sustainability, as well as the growing population and the big loss of food to spoilage after harvesting form a significant challenge to the food process engineer in the near future.

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