Food rheology: A personal view of the past and future

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ABSTRACT

In the last 20 years or so, rheology has become an increasingly important tool for food science as well as the food industry and is now used for a wide range of purposes, ranging from routine analysis in industry to more complex investigations of e.g. macromolecular interactions.

The following is a subjective summary and status of the development within the various areas of food rheology. The focus is on the rheology of dairy products, and most of the examples illustrating the development are from dairy science and industry.

Also included is a view into the possible future of food rheology, i.e. a commented description on some of the probable directions and applications

INTRODUCTION

A rough estimate of the interest in food rheology can be seen in Fig. 1, which shows results from searching Google™ Scholar for papers with the term ‘food rheology’ as well as papers with ‘food’ and ‘rheology’. There is little doubt that the amount of published material dealing with the area has been steadily increasing in the last 20 years or so – and no decline in the interest seems evident.

This estimate coincides well with my own experience: That food rheology has become a well established part of the toolbox for food scientists in academia as well as in industry. Hence I felt the need to look back

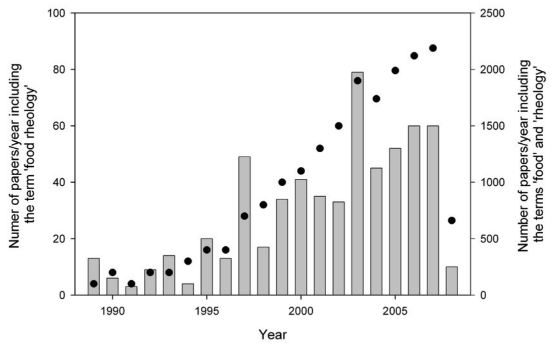

Figure 1. Number of papers containing the term ‘food rheology’ (bars) as well as ‘food’ and ‘rheology’ (black circles) found by searching Google™ Scholar, May 2008.

and evaluate the contribution rheology has made to food science, and also hazard a guess as to what future directions food rheology can be imagined to take.

Some of the areas that have received major attention are:

Rheology as a probe for macromolecular interactions in foods

Relation between measured instrumental (rheological) parameters and sensory perception

Using rheology to predict final food product quality.

Rheology as an integrated part of food ingredient development and verification

- Interfacial rheology for emulsions and foams
- Food process rheology
- Relations between rheology and food microstructure
- Rheology and oral processing

In the following I'll provide a few examples from the above areas to illustrate the applicability of rheological methods in food science.

RHEOLOGY AS A PROBE FOR MACROMOLECULAR INTERACTIONS

Rheology is a bulk method, usually, and does not provide direct evidence of macromolecular interaction. It is, however, a good investigative tool, illustrating phenomena that can subsequently be probed by other methods.

When rheology was applied initially to follow the acidification of milk, one of the questions was where the somewhat puzzling 'bump' in the phase angel (δ) came from[1]. Immediately after the gel point, δ decreases to below 20^o and then gradually increases to a maximum when the pH is approximately 5 and then steadily declines to a final value of $13\text{-}15^o$. This was later resolved to be a consequence of network formation facilitated by heat treated whey protein prior to total depletion of calcium from the casein micelles. In fact, it appears[2] that if network (i.e. gel) formation, irrespective of how it is induced, occurs at pH values above ~ 5, where almost all calcium will be on ionic form, the 'bump' in δ is evident, illustrating continuing depletion of calcium from the casein micelles.

Another case, where rheology gave the initial evidence for a surprising phenomenon, is our own discovery of nanotubular structures induced by limited proteolysis[3].

RHEOLOGY AND SENSORY PERCEPTION

There are numerous examples of studies dealing with the relation between measured instrumental (rheological and fracture) parameters and sensory perception of food.

Within our group we have paid much attention to establishing such relations for a variety of dairy foods. An example dealing with stirred yoghurt[4] will suffice to illustrate the complexity involved. We found that the sensory perception of creaminess in low-fat yoghurt depended mainly on oral viscosity and smoothness. Creaminess was not only a result of textural properties and hence was difficult to predict solely from rheological properties.

In the same study much improved predictions of oral viscosity measured using the Posthumus funnel were found by recording the mass of yoghurt exiting the funnel, illustrating that simple empirical measurements can be useful when dealing with more straight forward textural parameters than creaminess.

Certainly more dedicated data treatment can be used to extract information from empirical tests. The sensory crunchy- or crispiness of food can be related to the jaggedness of the force-displacement curve obtained in compression or cutting[5].

A recent review[6] dealing with biopolymer gels as model systems for understanding the relationships between food structure and sensory texture notes the need for more comprehensive coupling of sensory attributes with microstructural fracture and macroscopic rheological properties. Thus, in order to probe and understand the complex nature of food texture, studies are needed that incorporate analysis of food structure, mechanical properties and oral processing with sensory texture attributes[6].

USING RHEOLOGY TO PREDICT FINAL FOOD PRODUCT QUALITY

It is, of course, of major interest to food manufacturers to be able to predict final food quality from tests on raw materials or partially processed products. Consider, for example, frozen dough, where a recent study[7] has been able to correlate dough textural behaviour in compression with the quality of final bread samples. This gives producers the ability to intervene in the bread making process and make necessary adjustments.

Our own recent research shows that rheological measurements (oscillatory shear) performed on cheese powder suspensions can be used to predict the functionality of the cheese powders in cheese cracker manufacture[8].

RHEOLOGY IN FOOD INGREDIENT DEVELOPMENT AND VERIFICATION

As many ingredients are added to food products in order to control textural properties and ensure long shelf-life, it is not surprising that much research and development effort has been applied to using rheology for understanding and verifying the efficacy of various food ingredients.

Just considering our group, we have used rheology to probe food ingredients such as enzymes (e.g. transglutaminase, proteases including rennet, phospholipases)[9,10,11,12], milk protein preparations (e.g. whey protein concentrates and isolates, purified whey proteins, casein, caseinates)[4,13,14,15] and polysaccharides (exopolysaccharides and carrageenans)[16,17].

Rheology has, in combination with other methods, most certainly contributed in a major way to our understanding of the mechanism behind how ingredients act in the very complex systems that foods are.

INTERFACIAL RHEOLOGY FOR EMULSIONS AND FOAMS

Not only has bulk rheology become an integrated part of the toolbox of food scientists and developers. Interfacial phenomena are increasingly being recognized as being of major importance to the quality of many food products. Numerous studies have been conducted on simplified model systems in order to understand the behaviour of various surface active components at interfaces.

It is often not possible to directly relate the interfacial rheological properties to functionality such as foam or emulsion stability[15]. However, even in highly complex systems, interfacial rheology can be used to probe the mechanisms underlying phenomena observed in bulk. An example of this is the effect of adding phospholipase to cheese milk, where the resultant improved emulsification of fat into the cheese matrix and the observed higher (~ 3 %) yield can be related to interactions between protein and lyso-phospholipid and the increased ability of lyso-phospholipid to decrease surface tension[12].

FOOD PROCES RHEOLOGY

Food process rheology is often confined to the behaviour of liquid foodstuffs, though the tendency is increasingly to consider the response of both solid and liquid materials[18].

Monitoring viscosity online or in-line during food processing poses a number of challenges due to the complex rheological nature of typical fluid foods. Foods can for example be multiphase, elastic, shear thinning, fibrous, particulate and highly viscous. In addition, high temperature and pressure demands specific design of equipment and sanitary requirements must also be met[19]. A number of approaches have, however, proven successful for process viscometry in the food industry, either in pilot or full industrial scale. Methods used include tube, vibrational, rotational, hot wire, mixer viscometry, Ultrasonic Doppler Velocimetry, ultrasonic reflectance and diffusing wave spectroscopy[19].

It would appear that ultrasonics-based in-line rheometry could be developed into a valid method of process monitoring as it can be used for studying in-line the rheological properties of e.g. starch suspensions and gels[20]. A non-invasive Doppler ultrasound-based technique has for example been used for investigation of non-stationary flow in chocolate pre-crystallization[21] and the influence of seeded crystals, temperature, and flow velocity on the rheology of chocolate suspension was monitored on-line.

RELATIONS BETWEEN RHEOLOGY AND FOOD MICROSTRUCTURE

Much effort has gone into establishing relations between rheology and food microstructure. While the search for generic relations between microstructural elements in foods and the resultant textural properties has perhaps not been very successful, the combination of the two approaches had led to major insights into the factors governing structure formation in a wide array of diverse food products. This is even more apparent when the two methodologies are combined and used to probe dynamic changes in food structure.

The fracture dynamics of biopolymer gels, for example, can be characterized by using a tensile stage coupled to a confocal laser scanning microscope and image analysis[22,23].

In general, application of more advanced image analysis, including multivariate methods applied to whole images, is necessary in order to unravel to complex rheological behaviour of even simple food systems. Just visually differentiating between micrographs can be almost impossible and we have used multivariate methods to aid in this task[17,24].

An example of rheology and microstructure providing separate but supplementary information on dairy systems is the case of exopolysaccharide (EPS) producing strains of lactic acid bacteria in production of yoghurt. The specific chemistry (i.e. monosaccharide composition) of produced EPS affects how it interacts with the protein matrix in yoghurt and hence also the resulting microstructure. This is again reflected in the rheological and sensory properties, e.g. in the characteristic ropiness normally associated with EPS producing LAB. High ropiness is associated with direct interaction between EPS and protein, evident in the microstructure and reflected in the rheology[25].

RHEOLOGY AND ORAL PROCESSING

The complex flow, deformation and fracture taking place orally during mastication and mixing with saliva is a major challenge to food rheologists. Food is subjected to a range of mechanical and chemical processes in the mouth. It is fractured, diluted and broken down by saliva, heated or cooled, formed into a bolus and swallowed[26]. In addition people vary substantially in eating behaviour, and certainly oral physiology plays a role in food texture perception[26].

A useful simplification is to consider that oral processing of most semisolid and solid foods can be summarized as two opposing mechanical influences: forces that fracture food particles versus those that make them adhere to each other[27]. During ingestion or the early stages of mastication, the aim of processing solid food particles is usually to fracture them. Later on adhesion is desirable to form a bolus that can clear the mouth of isolated food fragments[27]. These processes are not function of any particular force (or stress) nor displacement (or strain) on food particles, but is instead controlled by energy.

It may, in fact, be incorrect to define e.g. hardness in terms of a given force. When food is assessed in the mouth, hardness appears to be associated with the conditions present just as a food particle starts to fracture[27]. Sensory hardness and crunchiness of fruit and vegetables are thus closely related to the stress required to initiate a crack running through the sample and to the resistance a material has to crack propagation. The implication is that in hard or crunchy foods the main fracture events must take place in the relatively small zone at the tip of a crack-starting notch[28]. Such a highly localized event could be identified very effectively by muscle spindles not possessing the ability to monitor he force itself[27].

Thus, in order to make additional headway in the area of oral processing and how it affects sensory texture perception, a multidisciplinary approach involving food physics (especially rheology), thermal physics, physiology, and psychology is called for[29].

THE FUTURE DIRECTIONS OF FOOD RHEOLOGY

Health issues have become an important point of concern in our society, as a large increase of diet-related diseases has evolved. This will naturally also influence the future directions and developments in food rheology.

Future foods should not only be a good source of nutrients and have high sensory appeal, but also contribute to the general well-being and health of individuals, indicating a strong need to control bio accessibility and target release of food components during gastrointestinal transit. A major challenge for food rheology in the future is thus moving rheology into the human body, i.e. the gastrointestinal (GI) tract in order to understand the interplay between food structure, oral processing and nutrient bioavailability and other phenomena related to human health such as survival of probiotic bacteria and delivery of bioactive ingredients.

A lot of effort has already been invested in understanding the microstructure of model food systems. It is now known how to create a variety of well defined microstructures even though the precise mechanism of their formation is in many cases not yet elucidated. The ability to control assembly of food macromolecules and minor components into a resultant food matrix is, in fact, rapidly becoming an integral part of food product design. Much less is known, however, about how food microstructure influences the break-down of food, e.g. during mastication or in the GI tract, or about the influence of the microstructure on the delivery and bioavailability of nutrients. In investigation of these issues rheology and understanding of fracture properties of food plays a key role.

Food microstructure affects bioavailability of nutrients, which are usually located in natural cellular compartments or within assemblies produced during processing. They thus need to be released during digestion in order to be absorbed in the gut. Bioactive ingredients as well have to be protected in order to achieve site-specific delivery and increase bioavailability. Carriers can be used to protect against degradation and to control the rate of release. The properties of carrier and encapsulation systems in relation to their performance in the GI tract are not as yet well described, and rheology can aid in the elucidation of this.

However, looking in isolation at specific food microstructures is not enough. The influence of industrial processing on the interaction between generated food microstructures and nutrient bioavailability has not been very well researched. There is a high degree of linkage between bioavailability and processing[30], but limited insight into how food microstructures can be designed and processed to ensure maximum bioavailability.

The focus areas for food rheology in the past will of course move with us into the future and bring novel insights as well as serve as a standard method for analysis in the industry. There are also several areas not discussed here that deserves attention, e.g. the rheology of individual food structures (nano-rheology as e.g. made possible by atomic force microscopy).

CONCLUSION – A CHALLENGE

The challenge for future food rheology is to aid in elucidating how human health and wellbeing is influenced by food structure and the break down of structure during oral processing and passage through the GI tract.

This entails further developing our understanding of how food structure is generated on the molecular and supramolecular level as well as how it is influenced and controlled by processing. It also necessitates knowledge of how such generated structures behave during storage, during oral processing and in the GI tract.

Rheology, in my opinion, can play a role in all of these areas but can not stand alone. As always a multidisciplinary approach is called for, and I trust future collaborations will include – but not be restricted to - food physics and chemistry, pharmacology, medicine, physiology, microbiology, anthropology and psychology.

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