FOOD RHEOLOGY

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Contents

Summary

Food includes a wide range of biological materials with diverse rheological character. They are mostly a mixture of different structures previously treated in this book: emulsions, suspensions, foams, gels, solutions and melts. This means that the food rheologist deals with complex fluids which often are substantially inhomogeneous. The variability in the biological food systems is large in contrast to synthetic, well characterized systems, and is an effect of cultivation conditions, species variations, processing and recipe. Nevertheless, rheological characterization is an important tool for development, optimization and processing of foods.

Food rheology to a large extent determines food texture. The perception of the food on touching or in the mouth depends not only on rheological flow properties, but also on solid particles, fracture moisture release and absorption etc. which is not rheology. Food processing is substantially influenced by the rheology of the raw materials. Heat treatment is a common operation where the rheological properties influences heat transfer as well as residence times in addition to the energy required for fluid transport. The rheological properties are also important for the mass transfer involved in drying, fermentation and separation operations.

Foods behave much like the corresponding non-food, model systems previously discussed in this book, but with a few exceptions, e.g. food dispersion particles are mostly non-spherical, flexible, interacting and have a broad size distribution. The continuous medium usually contains several solutes and is often non-Newtonian. Gels

are commonly formed from associating food polymers with physical crosslinking rather than by permanent bonds.

Fluid and viscoelastic foods often consist of weak structures since disintegration in the mouth is desirable. This also means that special attention has to be paid in food rheometry. The sample handling is especially important not to destroy the delicate structures before the actual measurement. Wall slip is another common feature, especially for fatty foods and food dispersions.

1. Introduction

Food rheology covers a wide range of fluids and semi-solid materials from dilute juices, through gels and emulsions to solid cheese and breads. Food is familiar to all and everybody can relate to the texture or consistency and thus get a feel for its rheological properties. Unfortunately familiarity sometimes also leads the notion that foods relate more to cooking than to science. When surveying the huge range of different rheological behaviors of foods one realizes quite the opposite – the science of foods is rather challenging. Most foods are complex, heterogeneous systems difficult to characterize experimentally and to describe theoretically. They often consist of phase separated mixtures of polymers, mixed colloid and polymers systems or cellular biological structures. The behavior of food obeys the laws of physics but often empirical descriptions are used rather than physical models due to the complexity.

Rheology is important for many aspects of foods:

- Physical characterization of fluid and semi-solid foods
- Process engineering and process design
- Development of new products
- Quality control during production and of final products
- Instrumental evaluation of sensory properties
- Indirect understanding of food microstructure

The physical conditions for food rheology generally are limited to atmospheric pressure, temperatures approximately ranging from -20°C to 150°C, observations times from fractions of a second to a shelf life of a year. There are obviously exceptions but the general composition of a food includes water and biopolymers which limit the heat treatment and even modern processing techniques do not significantly differ from the heat treatments used for thousands of years. There are exciting new processing techniques entering the market such as high pressure treatment with pressure approaching 1000 MPa which clearly goes beyond conventional cooking. The majority of the flow conditions for foods in processing and consumption involve laminar flow, mostly due to the high level of viscosity of foods. Again, there are exceptions e.g. during processing of low-viscosity fluids such as juices, milk and soups where turbulent flow dominates.

Despite the vastly different texture occurring in foods they can be treated in terms of the previously described fluids in this book: emulsions, suspensions, foams, gels, solutions and melts, or mixtures thereof. Foods which are sufficiently described as Hookean solids, such as crackers, dry extruded snacks, dry pasta and hard cheese, will not be dealt with here. Such elastic foods are sufficiently described by their fracture properties and by fracture mechanics.

2. Food Rheology vs. Food Texture

Food rheology is not equal to food texture but there is considerable overlap. The perception of the bolus of a chewed food in the mouth depends on the flow of the fluid and the disintegrated semi-solid food i.e. the rheology of the food. The perception also depends on the release or absorption of moisture and oil and grinding and fracture of solid particles, i.e. the texture. Similarly, the perception of a food item squeezed between the fingers depends on several factors – rheology, Hookean elasticity, fracture mechanics and tribology, all related to the food in question. Rheological properties are related to perceived texture but are not fully describing the picture.

The International Standards Organization (ISO) defines food texture in their standard for vocabulary for sensory analysis (5492/3) as “all the rheological and structure (geometrical and surface) attributes of a food product perceptible by means of mechanical, tactile, and, where appropriate, visual and auditory receptors” which further shows that rheology is an integral part of food texture. When a food is consumed different textural characteristics are perceived during the mastication cycle, from the first bite to the final swallow. During the dynamic process of mastication food is crushed and diluted with saliva and its temperature is brought to body temperature. The rheological properties of the food change due to temperature, dilution, disintegration and the action of enzymes in the saliva. The stresses acting on the bolus are compressive during chewing whereas shear stresses dominate during the flow in the mouth. The flow is predominantly extensional when the bolus is squeezed to the back of the mouth between the tongue and the pallet and there is a considerable extensional flow component during swallowing.

State	**Approximate particle mass [g]**	**Process**	**Location**	**Implement**
Whole cookie	20	Biting off	Mouth	Incisors
Mouth size portion	5	Grinding, crushing	Mouth	Molars
Swallowable paste (bolus)	0.01	Biochemical attach	Stomach, intestine	Acid, enzymes
Hexose sugar molecule	$3\ 10^{-22}$	Absorption	Intestines	–

Table 1. Steps in the comminution of a large cookie before absorption by the body. Adapted from Bourne, M.C. (1982) *Food texture and viscosity. Consept and measurement*, Academic Press, New York

During mastication the food is ground into a fine state and diluted by saliva as a preparation for digestion starting in the stomach. A portion of mouth size is about 5 g which is reduced by two to three orders of magnitude before swallowing. The size is further reduced in the stomach by another 20 orders of magnitude to start the biochemical processes of the digestion system. If the food is not reduced to molecular dimensions it will not be absorbed, but excreted. The size reduction is exemplified in Table 1 and clearly demonstrates the large range of particle sizes during mastication. The particle size directly affects the rheological properties of the bolus in the mouth and during swallowing.

3. Rheology of Food Dispersions

Common foods such as mayonnaise, dressings, tomato paste and baby food are dispersions, more precisely emulsions or suspensions. In addition, foods such as chocolate and marmalades are suspensions during processing, before they solidify to form the final product. The rheological behavior of dispersions can be described by parameters such as particle size distribution, particle concentration and inter-particle interactions (see *Suspensions, emulsions and foams*). Suspensions consist of solid particles in a fluid medium whereas emulsions consist of liquid droplets in a liquid medium, i.e. deformable particles. The common descriptor of dispersion systems is the volume fraction of particles, Φ, which varies from zero to the maximum packaging fraction Φ_m. The maximum packaging fraction depends on the arrangement of the particles as well as the particle size distribution and is for foods mostly $\Phi < 0.5$.

3.1. Suspensions

Many food dispersions are plant based such as vegetable pastes and juices. Most, but not all of them display shear-thinning viscous flow behavior. Some also display a yield stress under specific flow conditions. The rheology of suspensions has previously been described (see *Suspensions, emulsions and foams*) for non-food suspensions but food suspensions differ from non-food suspensions in several ways:

- The particles are mostly non-spherical, flexible and have broad multi-modal size distributions
- The particles in food suspensions are hydrated and show significant inter-particle interaction affecting the flow behavior.
- The continuous medium usually contains sugars, organic acids, salts and biopolymers, and sometimes display non-Newtonian behavior.

Plant food suspensions serve as a good example of the complex nature of food suspensions and will be elucidated in more detail. The above mentioned characteristics all apply and in addition the processing adds to the complexity by heat induced changes of the constituents and formation of complex particle sizes and size distributions. Viscous flow parameters and the concentration of solids are presented in Table 2 for a range of plant based suspensions.

Product	**% solids**	***T* [°C]**	***n***	***K* [Ns^n/m^2]**	**σ_{yield} [Pa]**	**α**	**β**
Apple sauce	87 – 99	25	0.15 – 0.40	7.4 – 77	18 – 46		
Apple concentrate						$2.8 \cdot 10^{-15}$	7.5
Apricot puree	69 – 72	4.5 – 60	0.28 – 0.46	3.5 – 46			
Banana puree	17.7	22	0.28	12			
Blackcurrant juice	35 – 64	5 – 60	1.0	2.4 – 500		$2.2 \cdot 10^{-9}$ – $8.9 \cdot 10^{-6}$	6.2 – 3.5
Grape juice	55 – 68	-10 – 40					
Lemon products	9.5 – 62		0.72 – 1	0.43 – 1.7	2.1		
Orange juice concentrate	59-65	30	0.30 – 0.40	0.26 – 0.45	0.49 – 0.78		
Tomato juice						81	2.4
Tomato paste			0.04	800		0.03	2.4

Table 2. Viscous flow parameters and concentration of solids for plant based suspensions including the constants α and β from eq. 1. Data from Gallegos, C., Franco, J. and Partal, P. (2004) "Rheology of food dispersions", *Rheology Reviews*, 19-65.

Tomato based suspensions are industrial commodities in the food industry and exist as paste, puree, concentrate and sauce. They are well studied due to being a commercial commodity. The skin and seeds are removed during processing and the amount of solids is increased to a varying degree depending on the type of product. Enzymes affecting pectin are inactivated by heat, also to a varying degree depending on product type. The products pass through several sieves during processing which determine the particle size as well as the particle shape.

Power Law behavior is usually sufficient for describing the shear thinning of these suspensions in industrial flow and the consistency index has been correlated to the solids content in several plant based suspensions by

$$K = \alpha\,(\text{total solids})^{\beta} \qquad (1)$$

where α and β are constants presented for a selected plant based suspensions in Table 2.

Yield stress models have also been used to describe the flow of plant based suspensions under specific flow conditions. The "ketchup effect" occurring when attempting to extract ketchup from a bottle is well known. At these flow conditions it is suitable to use a yield stress. Below the yield stress the ketchup remains in the bottle and does not flow out until the yield stress is exceeded. Herschel-Bulkley and variants of the Casson models (see *Non-Newtonian fluids*) have been used to describe the flow of plant based suspensions including the yield behavior.

Apart from flow processing parameters, the viscosity of the suspensions also depends on variety, cultivation conditions and heating, as it indeed does for many other foods. It is therefore difficult to present general facts on these systems. An example of this is the effect of particle size on suspension viscosity. Small particles are more affected than large ones by the ever present Brownian motion caused by the thermal energy in the system. When shearing a suspension the particles still line up in the direction of flow when hydrodynamic forces are large enough to dominate over Brownian motion. Since small particles are more sensitive to Brownian motion their suspension will retain a high viscosity to higher shear rates compared to a large particle suspension, thus displaying a higher apparent viscosity at a specific shear rate. This is not necessarily the case for plant based suspensions which in many cases have been reported to display higher viscosity for large particle suspensions than for small particle suspensions. The particle size was set by the screen size used in the preparation which also is responsible for the unexpected behavior. The screen does not only affect particle size but also particle shape. Elongated, more rod-like particles have higher resistance to flow thus giving higher apparent viscosity. Food systems are complex and great care have to be taken when attempting to explain their rheological behavior in terms of model system behavior.

Tomato pastes have been shown to have a mechanical spectrum similar to that found for other concentrated suspensions. They display G' substantially higher than G'' at ω in the range 10^{-1} – 10^{2} rad/s with a tendency towards a $G'-G''$ crossover at $\omega<10^{-2}$ rad/s and have therefore been classified as "weak gels". This further emphasizes the inter-particle interactions responsible for the unexpected suspension flow behavior as well as the observed yield stress.

3.2. Emulsions

Food emulsions are not too dissimilar compared to dispersions with equal parameters (volume fraction particles/droplets, size distribution, interaction, continues medium rheology). The dispersed droplets are generally more mobile and fluid than corresponding dispersed particles thus giving lower viscosity. However, with small droplet size and strong adsorption layers of emulsifier the droplets can actually be very rigid and such an emulsion would behave similar to a dispersion. Emulsions also lack a well defined close packing limit since the droplets can deform. Indeed, most food emulsions are highly concentrated resulting in droplet deformation and flocculation giving non-Newtonian behavior of the emulsion. For example mayonnaise, which is an oil-in-water emulsion may well exceed a packing fraction of 0.8. For increasingly higher packing fraction the emulsion will resemble a filled foam rather than an emulsion.

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Biographical Sketch

Mats Stading of Gothenburg, Sweden is an engineer by basic training with an MSc in Engineering Physics from Chalmers University of Technology, Gothenburg. Mats Stading also had a PhD in Food Science with a thesis entitled "Rheological Behaviour of Biopolymer Gels in Relation to Structure" at Chalmers University of Technology in 1993.

After a Post-doc at MIT in Boston, USA working in the area of tissue engineering he returned to a position as assistant professor in Food Science at Chalmers. He was then associate professor in polymer technology at the same university before joining SIK – The Swedish Institute for Food and Biotechnology in Gothenburg in 2000. After a shorter period as visiting professor at MIT he 2003 was appointed Adjunct Professor at Chalmers in Materials Science. He is presently also Manager of the Material Design group at SIK. He has numerous peer reviewed papers and conference proceedings and has supervised a number of MSc and PhD students. After moving from physics to food rheology he now combines materials science and rheology applied to foods and biopolymer materials.

Professor Stading has been active in the Nordic Rheology Society since its funding in 1992 and is presently the Nordic representative in the European Society of Rheology and in the International Committee on Rheology.