Rheological Challenges for the Food Industry

Jan Engmann

Nestlé Research Center, Vers-chez-les-Blanc, PO Box 44, 1000 Lausanne 26, Switzerland

ABSTRACT

Several key challenges for rheologists working in the food industry are presented. These range from pure material science problems (complex yield behaviour, fracture mechanics of "soft" materials, interfacial rheology) and interactions with solid surfaces (wall slip) to the probably biggest challenge: the effects of rheology on processes inside the human body. Finally, the need for enhanced teaching of advanced rheological concepts in the field is highlighted.

INTRODUCTION

Designing and controlling rheological properties of food and nutrition products is a key to their commercial success: these properties crucially affect product manufacture, distribution, convenience and sensory experience. Since the range of relevant rheological properties can be very broad and only well understood through advanced physical concepts, it is a challenge to achieve this task within the constraints of the industry. Food structures contain many types of soft matter structures, e.g. amphiphilic molecules, polymers, molecular complexes, micelles, colloidal particles, particulate gels, polymer gels and so forth[1,2] and "managing rheology" in foods from a purely phenomenological (as opposed to microstructural) perspective not very promising. The complex microstructure brings about specific challenges for the understanding of rheological behaviour of foods itself and for interaction with the different environments they experience during their life time.

SEVEN RHEOLOGICAL CHALLENGES

1. Characterisation, theory and use of wall slip phenomena

It is now quite well accepted that slip or "apparent slip" phenomena of liquid and semi-solid materials near solid surfaces are ubiquitous in food products[3]. This should come as no real surprise, since many food products are highly concentrated disperse systems (hard or soft suspensions, emulsions or foams), which are known to exhibit this type of behaviour. However, the practical consequence in most cases is that one merely tries to *eliminate* slip phenomena when performing rheometry, e.g. by using roughened surfaces, vane geometries and other special tools. This in itself is not trivial to do, but even where it is successful, it is only a first step. During processing and consumption of foods (e.g. flow from a bottle or tube, use of a spoon to dose a product, in-mouth perception), the slip characteristics may significantly affect, or even dominate the perceived behaviour and thus be vital to successful products. Likewise, pumping of "slippery" materials can not be optimally handled by simply ignoring the slip behaviour when choosing and running a pump. For this, we need a methodology to systematically characterise and understand the nature of wall slip (including its transient nature) and how it depends on the structural features (e.g. size and concentration of particles or droplets) of the surface and the food material (see Fig. 1).

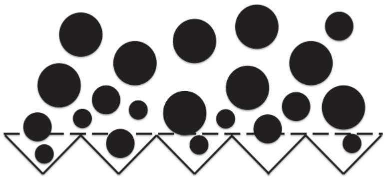

Figure 1. Size of microstructure elements relative to surface roughness is a key factor for wall slip.

2. Yield transition in "jammed" systems

The concept of a yield stress is widely used in the food industry. Less appreciated is the fact that a "sharp" (singular) yield transition is a strong idealisation of real material behaviour and that a more gradual (and history-dependent) transition from solid-like to liquid-like behaviour with frequent occurence of strongly localised deformation zones (see Fig. 2) is the reality in many food materials. The concept of a sharp transition (yield point) can be useful (for example in describing plug flow pipe flows), but often results in inconsistencies and ambiguities when different techniques are used to measure it. Apart from measurement artefacts, these issues result from the fundamentally history- and time-dependent nature of yielding. The idealisation completely fails where the complex transitional behaviour is actually important for the handling and perception of a product (e.g. spreading of butter, perceived texture of a dessert or beverage foam). Recent developments and reviews of this area[4-7] provide a stronger foundation for characterisation of these materials (including the terminology used), and the potential for improved physical food design seems considerable.

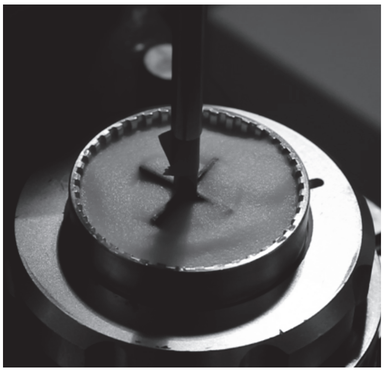

Figure 2. Yielding of a milk foam under stepwise increased shear stress using vane geometry.

3. Relation of time-dependent rheological properties to sensory texture

Partially linked to the second challenge is the question how to relate sensorial texture perception and product liking to key rheological properties of food products. This is a formidable challenge because of the complexity of human physiology (see also challenge #6) and the psychology of perception, which is a highly non-linear process. However, one may assume that substantial ground can be covered by adequately characterising time-dependent properties (linear and non-linear viscoelasticity, yield and thixotropic behaviour) of food products, which is rarely done. Two questions always arise beyond the common territory of steady-state viscosity and linear viscoelasticity: (a) which rheological material functions should be measured, i.e. which stress or deformation profile should be imposed and (b) which parameters should be extracted from the non-linear response and subsequently discussed. Large-amplitude oscillatory shear (LAOS) rheometry might be a powerful answer to both questions – it naturally covers linear viscoelasticity as well as the nonlinear domain and more recently, physically meaningful and robust parametrisations of non-linear response in large-amplitude oscillation have been proposed[8-11]. Modern rheometer software increasingly provides access to the raw periodic signals needed for this analysis and at least one algorithm (MITLAOS[12]) for such an analysis is freely available. Fig. 3 shows shear thinning, progressive reduction in shear viscosity and non-linear viscoelastic behavior of a food emulsion tested via LAOS cycling at a maximum shear deformation of 200 %.

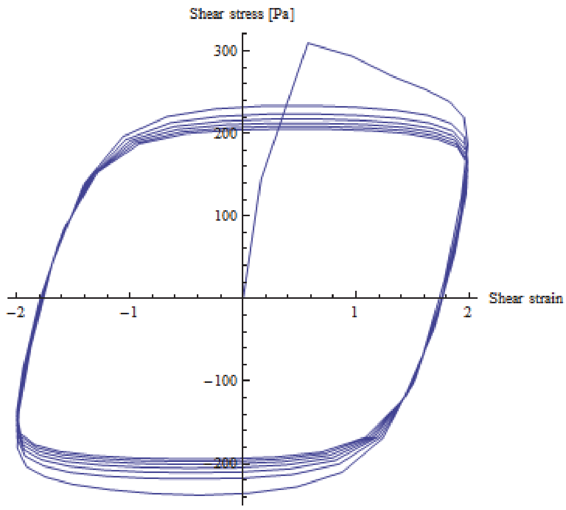

Figure 3. Large-amplitude oscillatory shear cycles for a food emulsion.

4. Interfacial rheology and its implications for food structure

Foods are typically "full of interfaces" and contain a variety of surface active materials which contribute to microstructure formation and stabilisation. Beverage foams, dairy products or mayonnaise are good examples. To understand and optimise the formation, stabilisation and breakdown of food structure, the way these interfaces evolve under specific external conditions needs to be characterised[13,14].

Real interfaces can have complex configurations in three-dimensional space (as well as a finite third dimension, i.e. thickness) and are naturally open systems, i.e. they can exchange material with the adjoining bulk phases.

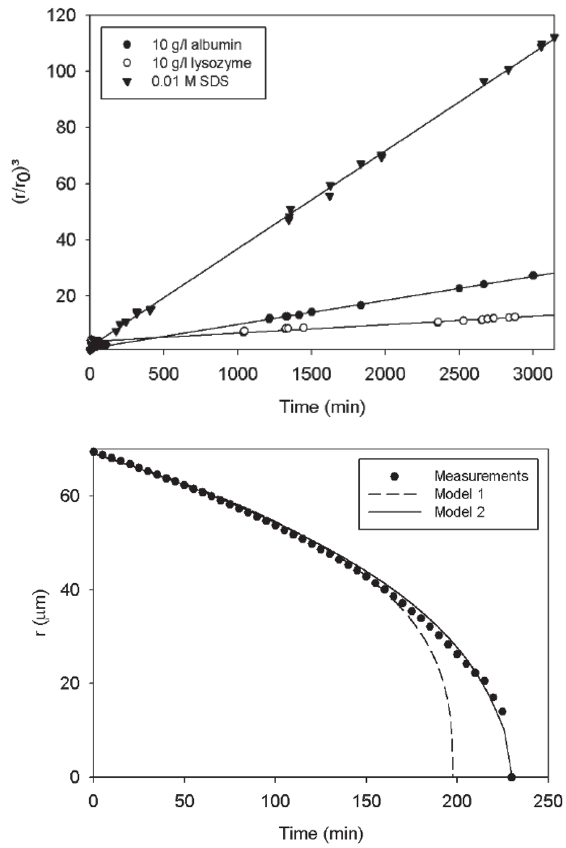

Figure 4. (a) Size of an air bubble evolving due to Ostwald ripening in favour of another (larger) bubble, for different emulsifiers (b) description of bubble growth through a model accounting for inerfacial tension only (model 1) and interfacial dilatational modulus (model 2). Van Hooghten and Verwijlen (2009)[15].

"Interfacial rheology" is therefore arguably an even more complex field to master than "classical" rheology. A solid theoretical framework to describe interfacial rheology exisits[16,17], but well-defined techniques allowing to "cleanly" observe interfacial kinematics and dynamics and to separate them from "bulk" behaviour are still an emerging field[18-20] which is likely to significantly improve our understanding and control of disperse food microstructure.

5. Solid mechanics and fracture mechanics

Solid mechanics is a well-established subject in mechanical engineering and classical materials science, but it has found very little application so far in the food industry, although it clearly has applications in process as well as in product design[21,22]. One reason is perhaps simply a lack of familiarity with solid mechanics in the food science community. However, both the characterisation and prediction of solid food properties are not trivial, even for relatively "simple" food materials. Unlike liquids, solid food materials usually have no mechanism to equilibrate towards a reference state over reasonable (and therefore useful) timescales. Apart from the difficulty of defining a reference state, this poses problems for the production of well-defined shapes (e.g. cylindrical or rectangular bars) of appropriate size that are needed for a well-defined mechanical characterisation unless inverse modelling techniques are used[23] – e.g. molding of samples to achieve these shapes may alter the internal microstructure as well as produce internal flaws leading to different fracture behaviour than the original material. As a consequence, very few material data are readily available for use in design calculations.

6. Biological flows and rheological changes in the human body

Rheological properties play an important role during the entire "lifetime" of a food product: assembling the ingredients into a product, dosing and packaging the product, transporting and storing the product and finally eating and digesting it. The product interacts with all these different environments during its lifetime (through exchange of momentum, energy and/or mass) and many of these aspects have been extensively studied in food science and engineering. Very little is still known, however, about the interactions of food structures with the human body during mastication, swallowing and digestion and our understanding is mostly qualitative[24-29]. The reasons for this are fairly obvious: the anatomy and physiology of the human body are very difficult to characterise quantitatively *in vivo* and even for quite simple aspects (e.g. basic dimensions and shape of the tongue and palate), characteristic values and natural variations are not easily established. Similarly, there are few elegant and non-invasive methods to follow the changes of a food bolus as it interacts with different parts of the body. Appropriate imaging (e.g. MRI, ultrasound, X-ray scans) and sensor technologies (e.g. manometry, impedance measurements) are, however, steadily improving, primarily driven by medical applications, and we may be gradually approaching an age in which many well-posed questions concerning mastication, swallowing and digestion can be answered with justifiable effort and cost.

Figure 5. MRI scan of head and neck region.

7. Rheology education in food science beyond "1-D rheology"

Undergraduate courses in food science or food engineering often include some basics of rheology. These are, however, often limited to the discussion of simple shear flows, thus avoiding the use of vector and tensor analysis. While "1-D rheology" is useful for certain process calculations (flow in pipes) and interpretation of structure-rheology relationships, it fails to explain many important phenomena in real process flows. Furthermore, it leaves a serious conceptual gap in appreciating the importance of more complex flows (and related non-Newtonian phenomena) for food processing and food properties. If not addressed, this gap can rarely be closed during professional practice. Since it is unrealistic for every food scientist and engineer to take a comprehensive training in continuum mechanics and tensor analysis, there is a need for better illustrating the consequences and usefulness of more "advanced" rheological concepts in the food area and better link it to the subject of engineering fluid mechanics, especially for graduate courses in food science and engineering.

ACKNOWLEDGMENTS

The author would like to thank all his colleagues at Nestlé Research for helping him to develop an understanding of the potential and limitations in using rheology to solve real problems in the food industry. For the particular challenges presented here, discussions with Adam Burbidge, Deniz Gunes, Chris Pipe, Marco Ramaioli, Tim Althaus, Benjamin Le Reverend and Chrystel Loret were extremely helpful.

REFERENCES

1. Mezzenga, R., Schurtenberger, P., Burbidge, A.S., Michel, M. (2005), "Understanding foods as soft materials", *Nature Material,* **4(10)**, 729-740.

2. Ubbink, J.B., Burbidge, A.S., Mezzenga, R. (2008), "Food structure and functionality: a soft matter perspective", *Soft Matter,* **4(8)**, 1569-1581.

3. Martin, P.J., Odic, K.N., Russell, A.B., Burns, I.W., Wilson, D.I. (2008), "Wall slip and rheology of an ice-cream foam", *Appl. Rheol.,* **18(1)**, 1-11.

4. Ovarlez, G., Rodts, S., Chateau, X., Coussot, P. (2009), "Phenomenology and physical origin of shear localization and shear banding in complex fluids", *Rheol. Acta,* **48(8)**, 831-844.

5. Møller, P.C.F., Fall, A., Chikkadi, V., Derks, D., Bonn, D. (2009), „An attempt to categorize yield stress fluid behaviour", *Phil. Trans. Royal Soc. A,* **367**, 5139-5155.

6. Møller, P.C.F., Mewis, J. Bonn, D. (2006), "Yield stress and thixotropy: On the difficulty of measuring yield stresses in practice", *Soft Matter*, **2(4)**, 274-283.

7. Mewis, J., Wagner, N. (2012), "Colloidal Suspension Rheology", Cambridge University Press, Cambridge, UK.

8. Ewoldt, R.H., Hosoi, A.E., McKinley, G.H. (2008), "New measures for characterizing nonlinear viscoelasticity in large amplitude oscillatory shear", *J. Rheol.*, **52(6)**, 1427-1458.

9. Hyun, K., Wilhelm, K., Klein, C.O., Cho, K.S., Nam, J.G., Ahn, K.H., Lee, S.J., Ewoldt, R.H., McKinley, G.H. (2011), "A review of nonlinear oscillatory shear tests: Analysis and application of large amplitude oscillatory shear (LAOS)", *Progr. Polym. Sci.*, **36(12)**, 1697-1753.

10. Läuger, J., Stettin, H. (2010), "Differences between stress and strain control in the non-linear behavior of complex fluids", *Rheol. Acta*, **49(9)**, 909-930.

11. Ewoldt, R.H., Winter, P., Maxey, J., McKinley, G.H. (2010), "Large amplitude oscillatory shear of pseudoplastic and elastoviscoplastic materials", *Rheol. Acta*, **49**, 191-212.

12. http://mechse.illinois.edu/research/ewoldt/research.html

13. Langevin, D. (2000), “Influence of interfacial rheology on foam and emulsion properties”, *Adv. Coll. Interf. Sci.*, **88(1-2)**, 209-222.

14. Murray, B.S. (2002), “Interfacial rheology of food emulsifiers and proteins”, *Current Op. Coll. Interf. Sci.*, **7(5-6)**, 426-431.

15. Van Hooghten, R., Verwijlen, T. (2009), „Control of coalescence and Ostwald ripening in structured emulsions“, Master’s thesis, Katholieke Universiteit Leuven.

16. Scriven, L.E. (1960), “Dynamics of a fluid interface Equation of motion for Newtonian surface fluids”, *Chem. Eng. Sci.*, **12(2)**, 98-108.

17. Edwards, D.A., Brenner, H., Wasan, D.T. (1991), “Interfacial Transport Processes and Rheology”, Butterworth-Heinemann, Boston.

18. Verwijlen, T., Moldenaers, P., Stone, H.A., Vermant, J. (2011), „Study of the flow field in the magnetic rod interfacial stress rheometer”, *Langmuir*, **15(2)**, 9345-9358.

19. Vandebril, S., Franck, A., Fuller, G.G., Moldenaers, P., Vermant, J. (2010), “A double wall-ring geometry for interfacial shear rheometry”, *Rheol. Acta*, **49(2)**, 131-144.

20. Miller, R., Fainerman, V.B., Wüstneck, R., Krägel, J., Trukhin, D.V. (1998), „Characterisation of the initial period of protein adsorption by dynamic surface tension measurements using different drop techniques”, *Coll. Surf. A*, **131(1-3)**, 225-230.

21. van Vliet, T. (2002), “On the relation between texture perception and fundamental mechanical parameters for liquids and time dependent solids”, *Food Qual. Pref.*, **13(4)**, 227-236.

22. Goh, S.M., Charalambides, M.N., Williams, J.G. (2003), “Large strain time dependent behavior of cheese”, *J. Rheol.*, **47(3)**, 701-716.

23. Goh, S.M., Charalambides, M.N., Williams, J.G. (2004), “Characterisation of non-linear viscoelastic foods by the indentation technique”, *Rheol. Acta*, **44(1)**, 47-54.

24. Burbidge, A.S. (2012), “Design of Food Structure for Enhanced Oral Experience”, in “Food Oral Processing: Fundamentals of Eating and Sensory Perception”, Wiley-Blackwell, London.

25. Le Reverend, B.J.D., Norton, I.T., Cox, P.W., Spyropoulos, F. (2010), “Colloidal aspects of eating”, *Current Op. Coll. Interf. Sci.*, **15(1-2)**, 84-89.

26. Chen, J. (2009), “Food oral processing – a review”, *Food Hydrocolloids*, **23(1)**, 1-25.

27. van Aken, G., Vingerhoeds, M.H., de Hoog, E.H.A. (2007), “Food colloids under oral conditions”, *Current Op. Coll. Interf. Sci.*, **12(4-5)**, 251-262.

28. Hutchings, J.B., Lillford, P.J. (1988), “The perception of food texture – the philosophy of the food breakdown path”, *J. Texture Stud.*, **19**, 103-115.

29. Nicosia, M., Robbins, J. (2001), “The fluid mechanics of bolus ejection from the oral cavity”, *J. Biomech.*, **34(12)**, 1537-1544.