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Application of Rheology in Food Engineering; Concentrated Food Emulsions and Dispersions

6.1 Introduction

Traditionally, foods have been classified as hard solids, soft solids and liquids. Some examples of these general physical categories are shown in Table 6.1.

Table 6.1 General categories of foods.

| General Category | Food Examples |
|------------------|-----------------------------------|
| Hard solids | Chocolate, biscuits, hard cheese |
| Soft solids | Butter, ice-cream, tomato paste |
| Liquids | Water, honey, ketchup, mayonnaise |

Many foods of commercial importance, such as baby foods, mayonnaise, salad dressings and plant food concentrates (orange, tomato, apple, etc.) are concentrated dispersions of solid (suspensions) or fluid (emulsions) matter in fluid media, which may behave as soft solids or highly non-Newtonian liquids. Rheology plays an important role in food manufacture and marketing [Barnes H; 2001], i.e. Design of handling systems, quality control and evaluation of sensory stimuli associated with oral and non-oral evaluation of viscosity [Rao M A; 1992]. Starting with processing, it is notorious that process variables determine the microstructure formed for a given formulation, and hence its rheology. Often, processing is itself affected by the rheology of the product, especially if it is very viscoelastic or very shear-thinning. When the final product is formed its rheology should be measured in a precise manner, accounting for any wall effects and selecting, for instance, the appropriate range of deformation rate for the particular application. A suitable constitutive equation should be selected, then, to fit the rheometry results. This step is still quite challenging for semisolids food products, taking into account their dramatic shear-thinning response and the probable appearance of instabilities in a significant range of shear rates [Bertola V, Bertrand F, Tabuteau H, Bonn D and Coussot P, 2003]. This suitable constitutive

equation can be used to calculate flows in other geometries, i.e. process equipment's, using Computational Fluids Dynamics. Finally, the measured product rheology should also be compared with the subjective consumer perception.

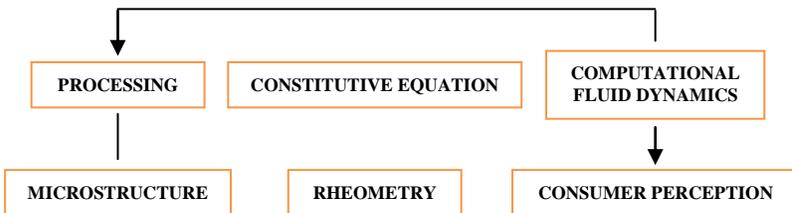


Figure 6.1 Important areas in the study of Food Rheology (reproduced from Barnes H; 2001).

6.2 Description

Although food scientists have some control over the final properties of a product, they must work within the physical constraints set by nature (i.e., the characteristics of the individual molecules and the type of interactions that occur between them). There is an increasing awareness within the food industry that the efficient production of foods with improved quality depends on a better understanding of the molecular basis of their bulk physicochemical and organoleptic properties (Baianu 1992, Kokini et al. 1993, Eads 1994). The individual molecules within a food emulsion can interact with each other to form a variety of different structural entities. A molecule may be part of a bulk phase where it is surrounded by molecules of the same type, it may be part of a mixture where it is surrounded by molecules of a different type, it may be part of an electrolyte solution where it is surrounded by counter ions and solvent molecules, it may accumulate at an interface between two phases, it may be part of a molecular aggregate dispersed in a bulk phase, it may be part of a three dimensional network that extends throughout the system, or it may form part of

a complex biological structure (Israelachvili 1992). The bulk physicochemical properties of food emulsions depend on the nature, properties, and interactions of the structures formed by the molecules. The structural organization of a particular set of molecules is largely determined by the forces that act between them and the prevailing environmental conditions (e.g., temperature and pressure). Nevertheless, foods are rarely in their most thermodynamically stable state, and therefore the structural organization of the molecules is often governed by various kinetic factors which prevent them from reaching the arrangement with the lowest free energy. For this reason, the structural organization of the molecules in foods is largely dependent on their previous history (i.e. the temperatures, pressures, gravity, and applied mechanical forces experienced during their lifetime). To understand, predict, and control the behaviour of food emulsions, it is important to be aware of the origin and nature of the forces responsible for holding the molecules together and how these forces lead to the various types of structures found in food emulsions. Only then will it be possible to create and stabilize foods that have internal structures that are known to be beneficial to food quality.

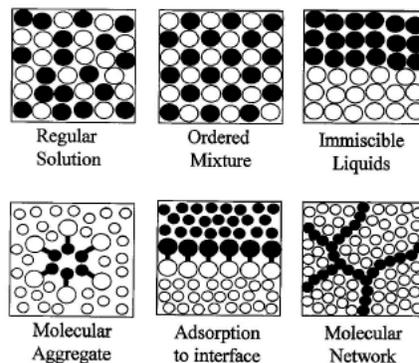


Figure 6.2 The molecules in food emulsions may adopt a variety of different structural arrangements depending on the nature of their interactions with their neighbours.

6.3 General Analysis

Emulsification is a complex unit operation in which many variables influence the processing and the final rheological characteristics of the product. The manufacture of emulsions usually requires the application of considerable mechanical energy. The two critical steps are the consecutive disruption of droplets and their coalescence, both of which are favoured by an intense agitation. Consequently, the improvement of the emulsification process requires the measurement of the droplet size of the dispersed phase and its polydispersity. Moreover, the emulsification process may be greatly affected by the viscous and viscoelastic properties of the continuous phase at which the disperse phase is added. One of the first studies on the influence of mechanical variables during processing was reported by Franco et al., [Franco J M, Guerrero A and Gallegos C; 1995] for emulsions stabilized by a mixture of macromolecular and low-molecular-weight emulsifier. Figure 6.3 shows the linear relaxation spectra of emulsions prepared with a rotor-stator turbine as a function of rotational speed and residence time. As can be observed the slope of the plateau region increases with the processing mechanical variables, because of the development of a three-dimensional network. This is also enhanced by a decrease in mean droplet size and polydispersity of the emulsion, yielding stronger inter-droplet interactions. As a result, stability against creaming was improved. Different results were obtained later on for emulsions stabilized by a sucrose ester non-ionic surfactant [Gallegos C, Sanchez M C, Guerrero A, Franco J M; 1996], which forms a gel-like structure in the continuous phase for a wide range of concentrations and temperatures [Madiedo. J. M; 1996]. As was previously mentioned, an increase in agitation speed or emulsification time also produces a decrease in droplet size and polydispersity. However, in this case, an increase in the agitation speed produced a decrease in the values of the dynamic viscoelasticity functions. The opposite

effect was found by increasing the emulsification time. Therefore, the viscoelastic properties of these emulsions depend on the balance between the formation of a larger interfacial surface and the breakdown of the gel-like structure of the continuous phase during processing. The influence of mechanical processing variables on vegetable protein stabilised emulsions is mainly affected by droplet size [Franco J M, Raymundo A, Sousa I and Gallegos C, J.; 1998]. An increase in emulsification time and, specially, agitation speed produces a decrease in the Saut é diameter and favours the development of an entanglement network, noticed by an enhanced development of the plateau region in the mechanical spectrum and a significant increase in the values of the dynamic functions (i.e. see figure 6.4). These authors also found an increase in emulsion viscosity and other textural parameters like firmness and adhesiveness.

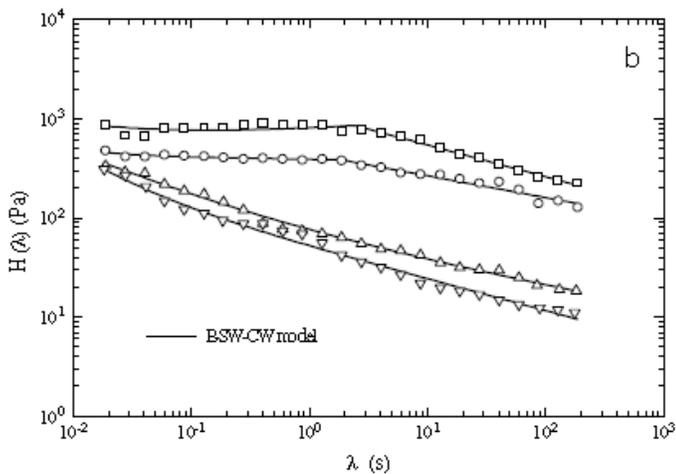


Figure 6.3 Influence of emulsification time and agitation speed on the relaxation time spectra of salad dressing emulsions: 8000 rpm – 5 min, ○8000 rpm - 3min, Δ 5000 rpm – 5 min, ▼ 5000 rpm – 3 min. Adapted from Franco J M, Guerrero A and Gallegos C; 1995.

Temperature is a crucial variable to be controlled during the processing of protein-stabilised emulsions. For instance, an increase in the temperature during

the emulsification, induced by the application of a severe mechanical energy, must affect the protein hydrophobicity [Raymundo A, Franco J M, Gallegos C, Empis J and Sousa I, *Nahrung*; 1998] and, consequently, favours the inter-droplet

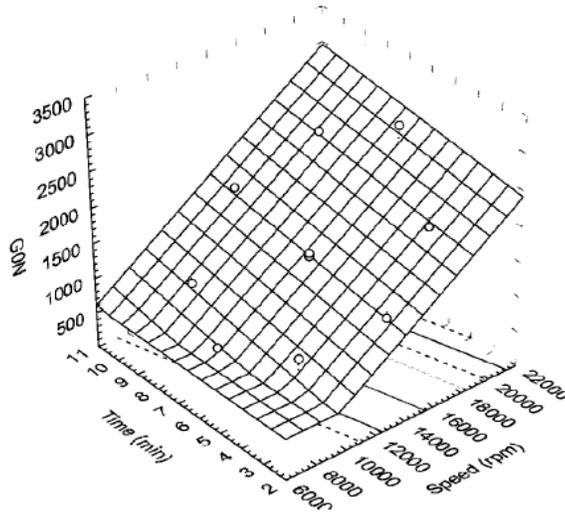


Figure 6.4 Evolution of the plateau modulus for lupin protein-stabilized emulsions prepared with different emulsification times and homogenization speeds (reproduced from Franco J M, Raymundo A, and Sousa I and Gallegos C, J.).

interactions. On the other hand, an increase in temperature or heating time favours the coalescence process, leading to larger droplet sizes and broader distributions, as found for pea-protein stabilised emulsions [Franco. J. M, Partal. P, Ruiz-Marquez D, Conde. B and Gallegos. C, J.; 2000]. However, a severe thermal treatment previous to emulsification leads to more viscous emulsions. Thus, for instance, the viscosity and the plateau modulus increases with temperature, specially up to temperature around 75 °C and then remain almost constant, in spite of higher droplet sizes, a fact that is related to the achievement of the protein extensive denaturation. The application of high temperatures during the emulsification process produces similar effects [Franco J M, Guerrero A and Gallegos C; 1995]. An even more severe previous thermal treatment on native egg yolk is the spray-drying process, usually required to

microbiologically preserve the final product, or as the first step previous to a cholesterol extraction process [Bringe N A and Cheng. J; 1995]. The rheology of spray-dried yolk stabilized emulsions is dramatically different to that found with native egg yolk-stabilised emulsions due to a significant denaturation of egg yolk lipoproteins, which confers a marked gel-like behaviour and significantly higher values of the linear viscoelastic functions to these egg product-stabilized emulsions [Guerrero A and Ball H R, J.; 1994; Moros J E, Franco J M and Gallegos C.; 2002]. The application of thermal treatments after emulsification may also have significant influence on the rheological behaviour of protein-stabilised emulsions. Dickinson and co-workers [Dickinson E and Yamamoto Y; 1996] have extensively studied, during the last few years, the rheological properties of heat-set whey protein-stabilised emulsion gels and the *in situ* gelation process through small-deformation oscillatory measurements. In all cases, the fresh emulsion was a very low viscous liquid-like system and became gel network by increasing temperature. Thus, a crossover between G' and G'' was noticed at a relatively high temperature. Chen and Dickinson [Chen. J. and Dickinson E, J.; 1998] investigated the effects of protein concentration and the volume fraction of oil phase on the viscoelastic properties of heat-set whey protein emulsion gels. They conclude that protein concentration is the main factor affecting gel strength. The dispersed oil droplets act as space fillers but also help to build up the gel matrix structure through interactions between protein molecules at the droplet surface and those in the gel matrix. The filler effects of oil droplets on the rheology of heat-set egg yolk, soy and milk protein stabilised emulsion were respectively studied with some detail by Dickinson and Chen, Anton et al., and Kim et al. Although a simplified van der Poel's equation [Smith. J. C, J.; 1975] to estimate the shear modulus of a particulate composite has been used by the authors, the fitting fails due to both oil droplet flocculation and droplet deformability. This thermo

rheological behaviour was shown by emulsions with relatively low volume fractions of oil phase. The improvement in the strength of highly concentrated gel-like emulsions, by means of thermo rheological treatments, was also studied by Moros et al [Moros. J. E, Cordobes. F, Franco. J. M and Gallegos. C; 2003]. They show how highly flocculated egg yolk-stabilised emulsions, in principle with a soft gel-like behaviour achieved during the emulsification process, are susceptible to improve their gel-like behaviour by applying different thermal treatments on fresh emulsions. Thus, for instance, the application of upward/downward temperature cycles, setting the maximum temperature at 67 °C, avoids emulsion breakdown and yield significantly higher values of the rheological functions in comparison to those found with fresh emulsions, in spite of the thermal induced droplet coalescence observed. As may be observed in figure 6.5, in the first region, which corresponds to temperature range comprised between 25 °C and 67 °C, the evolution of G' is typical of that found during an upward temperature ramp, an initial decrease of the dynamic functions up to around 45 °C and a subsequent increase up to around 70 °C, related to a head-induced rearrangement of the egg yolk lipoproteins located at the interface of oil droplets. In the second region, where temperature is kept constant at 67 °C for different elapsed times, G' shows a rapid increase and then levels off. If temperature is kept constant at 67 °C for 500 s (cycles B₃ and B₄) the values of G' are significantly higher than those obtained by cooling the sample immediately after the maximum temperature was reached (cycle B₁). On the contrary, when the sample was maintained at 67 °C for a much longer period of time, i.e. 1500 s (cycle B₂), a slight decrease in G' is shown. These results were explained taking into account the aggregation of denatured lipoproteins, mainly live tins and LDL. However, if the sample is maintained at high temperature during an extended period (cycle B₂) a subsequent significant coalescence of oil droplets may be observed (i.e. $d_{43} = 25.2$ matter the

application of cycle B2 versus $d_{43} = 16.4 \mu\text{m}$ after the application of cycle B₃). Finally, a further sample cooling produces a new increase in G' , mainly due to hydrogen bonding. On the contrary, the cooling rate seems not to affect the final value of the linear viscoelastic functions, as may be deduced from the comparison of the final values of G' after the application of cycles B₃ and B₄ respectively. Afterwards, the values of G' do not change by keeping constant temperature at 25 °C, which indicates an irreversibility of the gel reinforcement process. However, absolute values of G' after the application of these thermal treatments were significantly lower as compared to those found by others [Chen J and Dickinson E, J.; 1998; Chen J and Dickinson E.; 1999; Chen. J. and Dickinson. E; 2000], results that were obtained with milk protein-stabilized emulsions subjected to the same thermal treatments and containing similar protein concentrations, even with much lower fraction of dispersed phase, which indicates that egg yolk-stabilized emulsions are much less susceptible to enhance gel strength than milk protein systems.

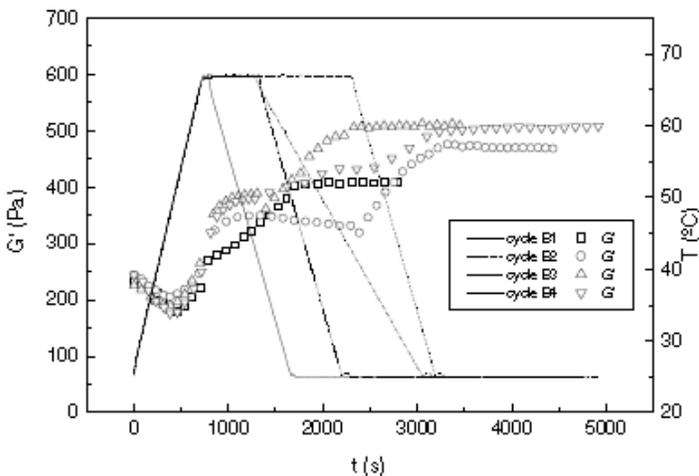


Figure 6.5 Evolution of G' with time, during the application of different cycles of temperatures, for an emulsion containing 70% (w/w) oil and 5% (w/w) egg yolk (reproduced from Moros J E, Cordobes F, Franco J M and Gallegos C; 2003).

The reversibility of heat-induced gelation was studied by Dickinson and co-workers, for casein ate-stabilised emulsions, through viscosimetry measurements [Dickinson. E. and Casanova. H; 1999; Dickinson. E. and Eliot. C; 2003]. They showed that a thermo-reversible gelation in the temperature range of 30-45 °C occurs mainly depending on pH and calcium ion content. They divided the emulsions, attending to the reversibility, in three categories (see figure 6.5): i) liquid like emulsions which remains liquid when heated, ii) liquid-like emulsions which become gels when heated, exhibiting an increase in viscosity of, at least, one order of magnitude and decreasing viscosity again when it was cooling back down, and iii) emulsions that show already a gel-like behaviour when emerging from the homogeniser, which present an increase in viscosity of several orders of magnitude on heating above 30 °C, without returning to low values on cooling back to ambient temperature. They presented a sort of phase diagram showing the different behaviours as a function of acid and calcium content. In addition to this, Chen and Dickinson [Chen J and Dickinson E; 2000] studied the effect of different programs of temperature on the reversibility of emulsions gels, attending to the evolution of the linear viscoelastic functions. As an example, they concluded that the application of a program 45 °C, 5 °C, and 45 °C on the emulsions leads to a temperature-reversible behaviour. G' and G'' increase on cooling to 5 °C and recover their original values on reheating to 45 °C. On the contrary, the program 5 °C, 45 °C, 5 °C produces a non-reversible rheological behaviour. Thus, they found G' values around 10 times higher than values before the application of the thermal treatment. An alternative to heat treatments is the high-pressure technology. The emulsifying and stabilising ability of some high-pressure treated vegetable and milk proteins were found inferior to those shown by the native proteins, which was attributed to an enhanced dissociation and/or aggregation through disulphide bridging [Galazka V B, Dickinson E and Ledward D A; 1999]. However, the viscoelastic parameters, i.e. the complex modulus, of

emulsions prepared with severely pressure-treated (up to 800 MPa) b-lactoglobulin are higher in a wide range of pH than those found with untreated systems, even more when a thickener agent was included in the formulation, probably due to the development of high-pressure-induced inter droplet macromolecular linkages [Dickinson E and James J D.; 2000]. In any case, high-pressure processing seems to be a gentler processing operation in terms of changes in droplet size and instability [Dickinson E and James J D, J.; 1998] On the contrary, high-pressure treatments prior to emulsification (600 and 400 MPa, respectively) on ovalbumin [Galazka V B, Dickinson E and Ledward D A, J.; 2000] or lupin protein [Chapleau N and de Lamballerie-Anton, M; 2003] clearly improve the emulsifying efficiency and stabilizing properties of emulsions. Concerning the rheological behaviour, Chapleau and de Lamballerie-Anton [Chapleau N and de Lamballerie-Anton, M; 2003] found that viscosity and G' and G'' values slightly increase with pressure, although the viscoelastic behaviour, typical of flocculated emulsions, was essentially the same.

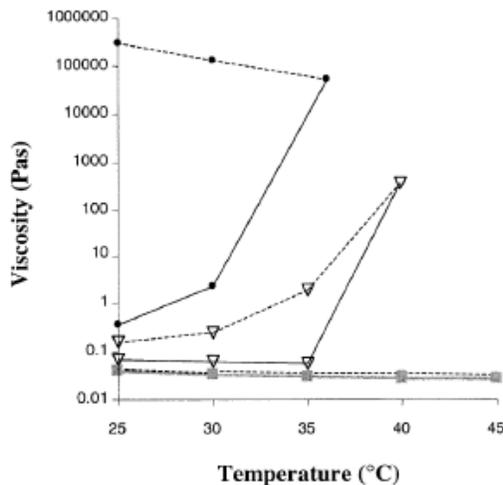


Figure 6.6 Examples of the three categories of emulsions attending to the thermo reversibility of the rheological behaviour. Solid lines: heating; dashed lines: back-cooling. ■: category i), ▼: category ii), ●: category iii). Reproduced from Dickinson E and Eliot C; 2003.

The influence of processing variables may be also studied by means of an *inside* rheological monitoring of the emulsification process [Edgar Chavez-Montes B, Choplin L and Schaer E; 2003]. The *in situ* rheological measurements were carried out in a small-scale semi-batch reactor, so called rheo reactor, equipped with a helical ribbon impeller adapted to a rheometer. An analytical method based on the Couette analogy allows to quantify correctly the torque-rotational speed to be transformed in the absolute rheological response, either under steady-state flow or in oscillatory regime [Ait-Kadi A, Marchal P, Choplin L, Chrissemant A S and Bousmina M, Can. J.; 2002]. The rheo-reactor not only provided real-time information during processing, but also allowed a complete rheological characterization of the final product without any sampling. Edgar Chavez-Montes et al. [Edgar Chavez-Montes B, Choplin L and Schaer E.; 2003] followed-up *in situ* the processing of one of the most complex food systems such as ice cream, consisting of an emulsion of milk-fat globules in a highly viscous continuous phase containing sugars, proteins and stabilizers together with ice crystals and air bubbles. Processing was divided in two crucial steps, foaming and subsequent freezing of mixes. They found that rheology of the incipient product was mainly influenced by the type and concentration of stabilisers. Figure 6.7 shows the evolution of specific viscosity with time during the foaming step for different blends of stabilisers and emulsifiers. In addition to this, a combination of two emulsifiers (i.e. Tween 20 and mono-and diglycerides) was necessary to produce a desired partial coalescence of fat globules, which is related to the melting resistance of ice creams.

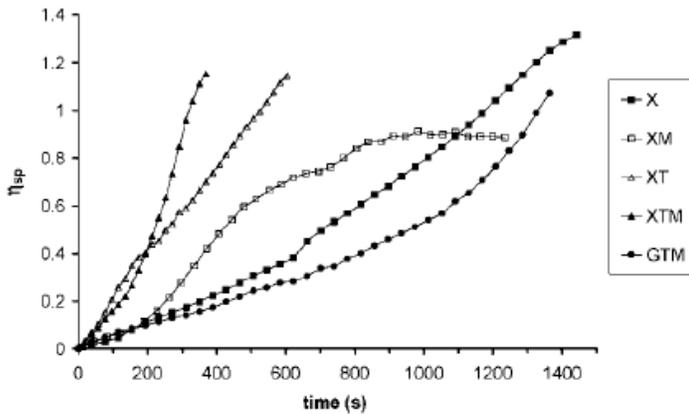


Figure 6.7 Evolution of specific viscosity during foaming of mixes stabilized with different thickeners and emulsifiers (reproduced from Edgar Chavez-Montes B, Choplin L and Schaer E; 2003).

6.4 Actualisation

The issue of wall slip requires special attention in relation to the understanding of the behaviour of disperse systems under shear conditions. At present, it is accepted that true slip at the wall does not occur during the flow of colloidal systems and, as Barnes [Barnes H A, J.; 1995] has pointed out, the term “wall depletion” is the most accurate way to describe this phenomenon in which the non-slip boundary conditions are not violated. Emulsions often show these effects due to the displacement of the dispersed phase away from solid boundaries, as for instance the walls of the sensor systems in aerometer or the walls of pipes or tubes, giving a depleted layer of liquid, which then acts as a lubricant. This leads to an apparent decrease in the measured bulk viscosity. In the case of emulsions, the deformability of the droplets and creaming enhance this effect. As has been detected in several food emulsions [Barnes H A, J.; 1995; Franco J M, Gallegos C and Barnes H A.; 1998] wall slip phenomenon is generally confined in a certain range of shear rates associated to constant values

of shear stress or, in other words, around a critical stress at which a sudden drop in viscosity takes place. The use of roughened plates or the vane geometry has been proposed as effective techniques for eliminating slip effects in emulsions [Pal R.; 2000]. However, in complex systems, such as food emulsions, this phenomenon is until now not fully understood from a micro-structural point of view. Franco et al. demonstrated that wall slip effects are strongly dependent on the composition and type of emulsion. Thus, for instance, a highly structured gel-like continuous phase dampens these effects, in contrast to oil-in-water emulsions with relatively low disperse phase volume fraction, in which creaming appears as a mechanism of instability. Sánchez et al. [Sanchez M C, Valencia C, Franco J M and Gallegos. C; 2001] proposed an empirical method to quantify the extension of wall slip as function of several structural parameters such as disperse phase fraction, emulsifier concentration and droplet size (influenced also by processing), according to the differences found in the flow curves obtained with both serrated and smooth geometries along the experimental range of shear rate or shear stress studied. More recently, Bertola et al. [Bertola V, Bertrand F, Tabuteau H, Bonn D and Coussot P, J.; 2003] have related the slip phenomena to the yielding behaviour and flow instabilities of emulsions. In addition to this, they demonstrated that slip does not occur when using rough surfaces by withdrawing the calculated shear rate due to slip from the data obtained with smooth surfaces. Then, flow curves almost exactly correspond to those obtained using rough surfaces. Although wall slip under the flow of food emulsions is a generally accepted phenomenon, some controversy appears in relation to the evidence of apparent wall slip in SAOS experiments. Ma and Barbosa-Cánovas and Plucinski et al. support the idea that no evidence of apparent wall slip in oscillatory shear is found for mayonnaises. On the contrary, Goshawk et al., which performed several tests with different plate-plate separations, found that the values of the linear viscoelastic functions, at a

given frequency, decrease as the plate-plate separation decreases, indicating that mayonnaise tested exhibits wall slip under SAOS, fact that is even surprising for the authors. Pal also detected that the oscillatory response of emulsions is strongly influenced by slip effects not only quantitatively but also from qualitative point of view since, in some cases, a solid like behaviour was found using the serrated plate geometry whereas a fluid-like response was obtained with smooth cone-plate geometries for the same emulsion. In addition to this, the linear viscoelastic range was clearly influenced by wall slip.

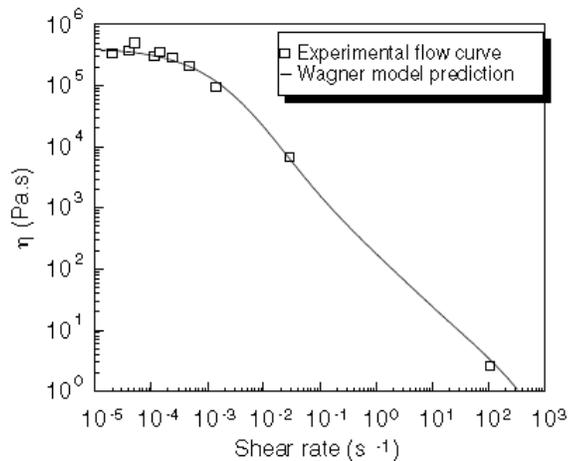


Figure 6.8 Prediction of steady viscous flow for an oil-in-water emulsion containing 65% oil and 3% lupin protein.

6.5 Discussion

Many natural and processed foods consist either partly or wholly as emulsions or have been in an emulsified state at some time during their production; such foods include milk, cream, butter, margarine, fruit beverages, soups, cake batters, mayonnaise, cream liqueurs, sauces, desserts, salad cream, ice cream, and coffee whitener (Friberg and Larsson 1997, Krog et al. 1983, Jaynes 1983, Dickinson

and Stainsby 1982, Dickinson 1992, Swaisgood 1996). Emulsion-based food products exhibit a wide variety of different physicochemical and organoleptic characteristics, such as appearance, aroma, texture, taste, and shelf life. For example, milk is a low-viscosity white fluid, strawberry yogurt is a pink viscoelastic gel, and margarine is a yellow semisolid. This diversity is the result of the different sorts of ingredients and processing conditions used to create each type of product. The manufacture of an emulsion based food product with specific quality attributes depends on the selection of the most appropriate raw materials (e.g., water, oil, emulsifiers, thickening agents, minerals, acids, bases, vitamins, flavours, colorants, etc.) and processing conditions (e.g., mixing, homogenization, pasteurization, sterilization, etc.). Traditionally, the food industry largely relied on craft and tradition for the formulation of food products and the establishment of processing and storage conditions. This approach is unsuitable for the modern food industry, which must rapidly respond to changes in consumer preferences for a greater variety of cheaper, healthier, and more convenient foods (Sloan 1994, 1996; Katz 1997). In addition, the modern food industry relies increasingly on large-scale production operations to produce vast quantities of foods at relatively low cost. The development of new foods, the improvement of existing foods, and the efficient running of food-processing operations require a more systematic and rigorous approach than was used previously (Hollingsworth 1995). Two areas which have been identified as being of particular importance to the improvement of food products are:

- Enhanced scientific understanding of food properties.

An improved understanding of the factors that determine the bulk physicochemical and organoleptic properties of emulsions will enable manufacturers to create low-cost high-quality food products in a more systematic and reliable fashion (Kokini et al. 1993, Rizvi et al. 1993).

- Development of new analytical techniques to characterize food properties.

The development and application of new analytical techniques to characterize the properties of emulsions are leading to considerable advances in research, development, and quality control (Dickinson 1995a, b; Gaonkar 1995). These techniques are used in the laboratory to enhance our understanding of the factors which determine the properties of foods and in the factory to monitor the properties of foods during processing in order to ensure that they meet the required quality specifications.

Emulsion science is a multidisciplinary subject that combines chemistry, physics, and engineering (Sherman 1968a; Becher 1957, 1983; Hiemenz 1986; Hunter 1986, 1989, 1993; Evans and Wennerstrom 1994). The aim of the emulsion scientist working in the food industry is to utilize the principles and techniques of emulsion science to enhance the quality of the food supply and the efficiency of food production.

6.6 General Recommendations

- Food researchers and manufacturers should strive to have an improved understanding of the factors that determine the bulk physicochemical and organoleptic properties of emulsions that will enable manufacturers to create low-cost high-quality food products in a more systematic and reliable fashion.
- Producers should adhere and comply with national standard bodies through established analytical procedures, regulations and standards.
- There should be concerted effort to promote the development and application of new analytical techniques to characterize the properties of

emulsions leading to considerable advances in research, development, and quality control.

- A more systematic and rigorous approach is needed in the development of new foods, the improvement of existing foods, and the efficient running of food-processing operations.

6.7 Conclusion

Most food emulsions are much more complex than the simple three-component (oil, water, and emulsifier) systems. The aqueous phase may contain a variety of water-soluble ingredients, including sugars, salts, acids, bases, surfactants, proteins, and carbohydrates. The oil phase usually contains a complex mixture of lipid-soluble components, such as triacylglycerol's, diacylglycerols, monoacylglycerols, free fatty acids, sterols, and vitamins. The interfacial region may contain a mixture of various surface-active components, including proteins, phospholipids, surfactants, alcohols, and solid particles. In addition, these components may form various types of structural entities in the oil, water, or interfacial regions, such as fat crystals, ice crystals, protein aggregates, air bubbles, liquid crystals, and surfactant micelles. A further complicating factor is that foods are subjected to variations in their temperature, pressure, and mechanical agitation during their production, storage, and handling, which can cause significant alterations in their overall properties. It is clear from the above discussion that food emulsions are compositionally, structurally, and dynamically complex materials and that many factors contribute to their overall properties. Much of our knowledge about these complex systems has come from studies of simple model systems. Nevertheless, there is an increasing awareness of the need to elucidate the factors that determine the properties of actual emulsion-based food products. For this reason,

many researchers are now focusing on the complex issues that need to be addressed, such as ingredient interactions, effects of processing conditions, and phase transitions (Dickinson 1992, 1995b; Dickinson and McClements 1995; Dalgleish 1996a; Hunt and Dalgleish 1994, 1995; Demetriades et al. 1997a, b).

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