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19

Relevance of Rheological Properties in Food Process Engineering

J. Vélez-Ruíz

CONTENTS

Abstract

Basic aspects related to the rheology of foods are introduced, including the definition of rheology, stress and strain concepts, as well as the classification of food materials. Physical relationships between force, deformation, and material properties or rheological properties, as well as the most known rheological models, are mentioned. More commonly used rheological techniques are briefly commented on regarding their main features: rotational rheometry, tube rheometry, back extrusion rheometry, extensional viscometry, and squeezing flow rheometry, as well as mixer viscometry. Mainly, flow properties and their relation to food process operations are discussed; studies in food process engineering, momentum transfer operations, heat transfer processes, mass transfer unit operations, and physical-structural changes are presented. Momentum transfer operations and their relation to flow properties of liquid materials are established; and the relationships between rheological parameters and food transport systems, mechanical separations, mixing, and pumping are emphasized. For heat transfer operations, the influence of rheological properties such as apparent viscosity, consistency coefficient, and flow behavior index are related to the heat transfer coefficient,

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presenting four representative equations developed and proposed by recognized authors. Similarly, in mass transfer operations, exemplified by spray drying and fermentation, the role of rheological behavior and its influence on process performance are mentioned. Finally, the relationship of structural changes and/or physical changes to the rheology of food products and components are briefly discussed.

19.1 INTRODUCTION TO FOOD RHEOLOGY

The goal of this chapter is to present a general overview of the rheology applied to food materials, with emphasis on the relationship between rheological behavior and food process engineering.

Rheology, defined as the science of flow and deformation of materials, is a fundamental interdisciplinary science that has been gaining importance in the field of foods. According to Rao,[1] Steffe,[2] Holdsworth,[3] Vélez-Ruiz and Barbosa-Cánovas,[4] Bhattacharya et al.,[5] and Vélez-Ruiz,[6] among others, there are numerous topics of interest to the food industry related to rheology, such as

- process engineering applications involved in equipment and process design
- physical characterization of liquid and solid foods
- development of new products or reformulation
- quality control of intermediate and final products
- correlation with sensorial evaluation
- understanding of food structure

Rheology can be used to characterize not only flow behavior of biological and inorganic materials, but also structural characteristics. Flow properties, such as viscosity, yield stress, thickness, pourability, softness, spreadability, and firmness, contribute substantially to facilitate transport and commercial processing as well as to promote consumer acceptance. Insight into structural arrangement helps to predict behavior or stability of a given material with storage, change in humidity and temperature, and handling.[7] Consequently, basic rheological information on materials is important not only to engineers but also to food scientists, processors, and others who might utilize this knowledge and find new applications.

Although food exists in a variety of forms, solids and liquids are of primary importance in food rheology. Many foods are neither solid nor liquid but exist in an intermediate state of aggregation known as semi-solid. As a consequence of the complex nature and lack of a precise boundary among solids and semi-solids, many foods may exhibit more than one rheological behavior, depending on their specific characteristics and the measuring conditions used during physical characterization. Deformation may be conservative or dissipative, depending on whether it is related to solids or liquids. Flow is a time-dependent form of deformation and, consequently, is more related to fluids.[8]

Two mechanical parameters (stress and strain) are the basis for material classification, from a rheological viewpoint, into three recognized groups: elastic, plastic, and viscous. Mohsenin,[9] based on the physical response of biological material to a given stress or strain, expressed a paramount visualization of rheology using three fundamental parameters: force, deformation, and time. This general classification is outlined in Figure 19.1. Accordingly, the specific relationship developed between an applied stress and the resulting deformation of the material is known as a rheological property.[10]

A wide range of models are available for the rheological characterization of foods. According to Holdsworth,[3] the rheological models may be divided into three main groups: *time-independent models*, including Bingham, Power Law, and Herschel–Bulkley; *time-dependent models,* such as Carreau, Hahn, Powell–Eyring, and Weltmann; and *viscoelastic* models, with Kelvin–Voigt element and Maxwell body being the best known. Certainly, there exist other, less popular models in food products, and others specifically applied to fit the effect of concentration and temperature.

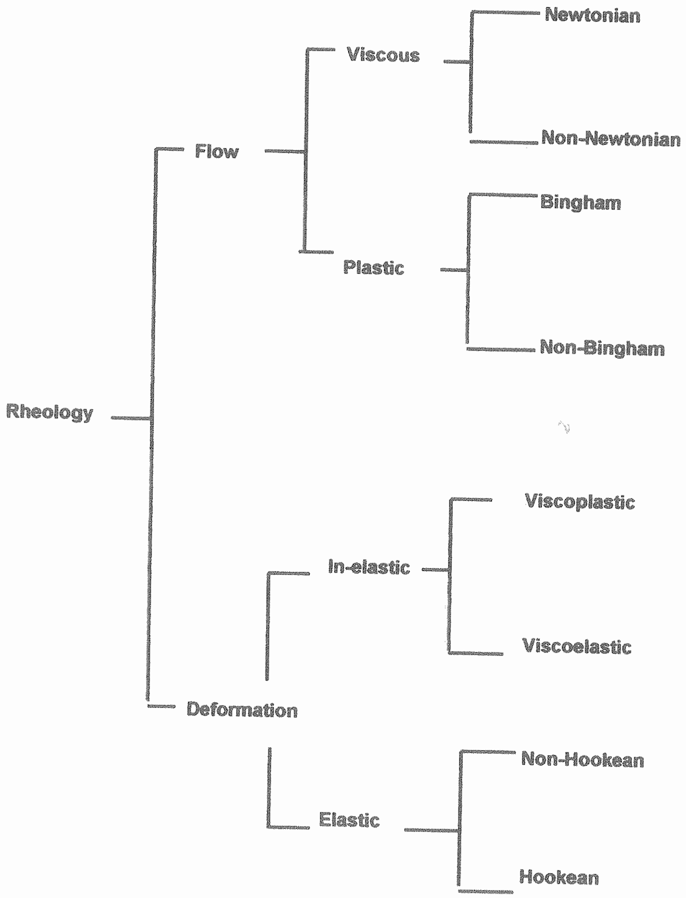

Figure 19.1 Rheological classification of food materials.

In rheology, *strain* and *stress* are two relevant physical variables that need to be considered when a material deforms in response to applied forces. Strain represents a relation of a change in length with respect to the original dimension. This parameter is essentially a relative displacement, and there are many definitions associated with this concept. For instance, the engineering strain is expressed by the following equation:[2,11,12]

$$\varepsilon_c = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} \tag{19.1}$$

where ε_c = engineering strain, also called Cauchy strain
ΔL = change in length
L = final length after deformation of the material
L_0 = original length before deformation

This definition is expressed in terms of a simple shear. Strain is determined by displacement gradients, and strain rate by velocity gradients. Strain and stress are tensor quantities and are represented by nine components.[10,13]

Stress that relates the magnitude of the force over the surface of application can be compressive, tensile, or shear, depending on how the force is applied. Nine separate components are required to adequately describe the state of stress in a material.[2,10,14] The stress at any point in a body may be represented by the following matrix:

$$\tau_{ij} = \begin{bmatrix} \tau_{11} & \tau_{12} & \tau_{13} \\ \tau_{21} & \tau_{22} & \tau_{23} \\ \tau_{31} & \tau_{32} & \tau_{33} \end{bmatrix} \tag{19.2}$$

where τ_{ij} is the stress tensor; the first subscript indicates the orientation of the face upon which the force is acting, and the second subscript refers to the direction of the force. This matrix may be simplified, depending on each specific physical system. For instance, in steady-simple shear flow, also known as *viscometric* flow, the matrix is reduced to only five components.[2,10]

A deformed body, as a result of an applied force, will develop internal stresses and strains that may be of various types.[15] The relationship shown by any food material between applied stress and resulting strain defines the *rheological properties of the material*. These relationships can be expressed either empirically or in terms of a rheological equation of state.[10] Figure 19.2 illustrates the correspondence between the physical forces and stress (τ), as well as the functional relation between deformation and strain (γ) and shear rate (strain/time).

There exists a particular approach in which the rheological behavior of a material is analyzed on a simplified deformation called *single shear* or *uniaxial* deformation. This approach is the basis for many rheological measurement techniques and permits the characterization of many food materials.[10,16]

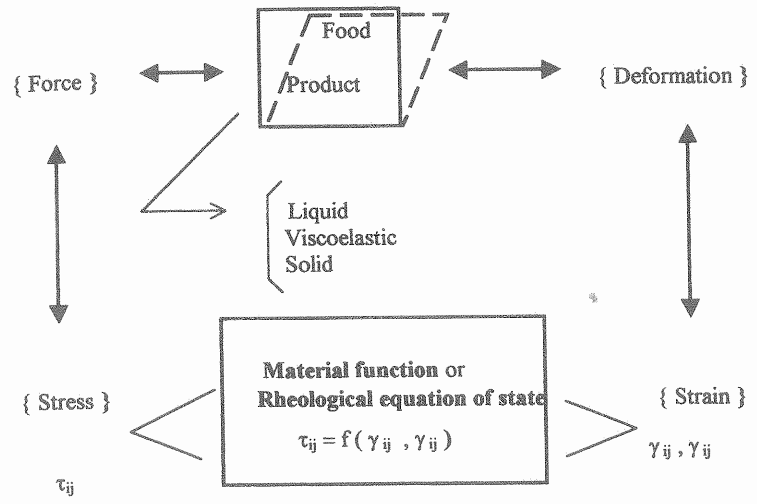

Figure 19.2 Physical relationships between force, deformation, and material properties.

19.2 MEASURING TECHNIQUES

Measuring the rheological properties and identifying the rheological behavior of food materials is necessary when employing any of the available commercial instruments that allow objective characterizations. The accuracy of these rheometers has been improved due to the incorporation of microcomputer technology and frictionless devices.

Based on their elemental geometry, the existing *common instruments* are divided into two major groups (rotational class and tube class[2,7]), but there are other rheometric approaches that have not been completely developed and therefore are not commercially available. These include back extrusion flow,[17,18] extensional viscometry,[19] mixing devices of various kinds,[20] and squeezing flow.[21] Each group of rheometers has advantages and disadvantages that must be considered whenever a rheological characterization of food systems is carried out. The selection of a rheometer for a particular task is a matter of great importance.

In food rheology, the *rotational type* is more commonly used than tube fixtures.[22] These rheometers are most suited for low-viscosity fluids,[23] and they have three main performance features:

1. A uniform shear rate may be applied.
2. The effect of time on the flow behavior can be followed.
3. Different geometries may be utilized: concentric cylinders, cone and plate, and parallel plates.

Most oscillatory or dynamic experiments are carried out in these rheometers. On the other hand, *tube viscometers* have been broadly used in flow characterization of different viscous foods such as fruit purees and juices, vegetable concentrates, gum solutions, and food dispersions. Tube viscometers that apply higher shear rates than rotational instruments can be easily manufactured following basic recommendations; therefore, they are simple and low-cost equipment, with several limitations.[24–28]

In *back extrusion,* the technique is simple and requires a texture meter, such as the Instron Universal Testing Machine or a similar instrument. Back extrusion requires graduated cylinders to hold the samples and plungers. Osorio and Steffe[18] developed mathematical relationships for the rheological characterization of Newtonian and power law food fluids. This approach is also known as *annular pumping,*[18] or the compression-extrusion test,[29] and it offers a good measuring alternative.

In many industrial processes (e.g., blow molding, dough sheeting, extrudate expansion, fiber spinning, flow through porous beds, mouth feel and swallowing of beverages, food spreading, and vacuum forming), it has been recognized that elongational deformation is the most important type of deformation.[23,30] Therefore, *elongational* or *extensional deformation* has been developed as a proper technique for rheological characterization of some food materials.[30] Data and applications of extensional deformation in foods are scarce. This technique is adequate for foods with proteins and polysaccharides and requires a generation of controlled extensional flows for rheological measurements.[19,23,30]

Squeezing flow viscometry, as a variation of the extensional flow measuring, is based on compression of a fluid material between two parallel plates. This type of measurement has been mathematically analyzed by Campanella and Peleg,[31] who generated the respective equations for lubricated squeezing flow. Fluids with high viscosity, such as cheese,[32] peanut butter,[31] mustard, mayonnaise, and tomato ketchup,[33] have been tested to evaluate their rheological properties.

The application of *mixing impellers* for the estimation of rheological parameters has been proposed by various authors.[34–40] Mixers have often been applied in rheological studies for fermentation processes. Particularly, the helical ribbon impeller has been very useful for complex fluids and suspensions, generating stable process viscosity values and avoiding phase separation,[20] a very common flow problem in food dispersions. Unfortunately, the adoption of mixer viscometry techniques has been limited because of the development of complex flow and the high costs of the equipment.

Rao[41] established that, due to the complex composition and particular structure of foods, approaches to characterizing a food's rheological behavior may be classified into five methods: empirical, phenomenological (including fundamental and imitative), linear viscoelastic, nonlinear viscoelastic, and microrheological. In the case of foods, empirical and phenomenological approaches have been predominant in those studies associated with flow properties.[41,42] With respect to viscoelastic nature, the approaches mainly include fundamental and linear viscoelasticity; most food systems are considered to be linear viscoelastic materials at small strains. Nonlinear viscoelastic materials exhibit physical properties that are a function not only of time but also of the magnitude of applied stress.[43]

On analyzing the published studies, one may observe that there are four main directions in rheological research.[23]

1. Description of the macroscopic phenomena developed during the deformation of materials
2. Explanation of the phenomena from a molecular point of view
3. Experimental characterization of parameters and functional relationships describing these phenomena
4. Practical application of the aforementioned directions

19.3 RHEOLOGICAL STUDIES IN FOOD PROCESS ENGINEERING

After commenting on some aspects of food rheology, it is interesting and important to identify some of the food process engineering operations in which flow and viscoelastic properties play an outstanding role. Those unit operations may be grouped in four areas:

1. Pipeline transport, mixing, pumping, and mechanical separations
2. Heat transfer operations such as heating, cooling, and evaporation
3. Mass transfer processes such as air drying, fermentation, osmotic concentration, and membrane separations
4. Physical changes during processing and tailoring the consistency and textural characteristics of foods

19.3.1 MOMENTUM TRANSFER OPERATIONS

Rheological properties of fluid foods are intimately related to power consumption, possibly the most important design parameter for momentum transfer operations involved in food processing. Although there have been advances in correlating the rheological behavior of non-Newtonian foods and power requirements or pressure drop, it is still a research field that needs more studies, mainly when some large-size particles are suspended in the fluid.[44]

Mechanical energy losses due to friction may be expressed by Equation (19.3),[45] which includes the energy losses due to fittings.

$$E_f = \frac{2 f u^2 L}{g_c D} + \sum_{i=1}^{n} \frac{k_f u^2}{2 g_c} \tag{19.3}$$

where E_f = energy loss per unit mass due to friction
f = Fanning friction factor
u = mass average or bulk velocity
L = total pipeline length
g_c = proportionality factor or constant (1.0 in SI, 32.2 in FPS)

D = internal diameter
k_f = friction loss coefficient
i = fitting

Other works have analyzed the influence of rheological properties on less important engineering design parameters. For instance, Li[46] studied the effect of the flow behavior index on the hydrodynamic entrance lengths in laminar falling films.

Some representative works related to momentum transfer in food process engineering are summarized in Table 19.1.

TABLE 19.1
Rheological Studies Related to Pipeline Transport and Pumping Needs

Ref./year	Material/experimental	Purpose/hypothesis	Important remarks
47/1971	–Dilatant starch system –Laminar flow	Study of flow through pipelines and fittings	Non-Newtonian fluid (NN) influences frictional losses.
48/1973	–CMC and starch solution –Mixing	Power consumption of non-Newtonian fluids	Development of empirical equations for power needs.
28/1980	–Pipe transportation of minced fish paste	Evaluation of pressure losses of a Bingham plastic food.	Pressure losses were related to rheological nature of minced fish
49/1984	–Non-Newtonian fluids –Theoretical approach	Expression to calculate kinetic energy	Mathematical and graphical solutions for kinetic energy evaluation.
50/1984	–Applesauce –Evaluation of pressure loss	Expression to evaluate frictional losses through fittings	Friction loss coefficients correlated to Reynolds number
51/1986	–Herschel–Bulkley fluids –Theoretical development	Determine optimum economic diameter	Optimal diameter estimated from mass, economic, and flow parameters.
52/1986	–Agitated systems –Newtonian (N) and non-Newtonian fluids	Effect of rheological behavior on power consumption	Develop empirical correlations for pseudoplastic fluids.
53/1987	–Friction factors for non-Newtonian fluids –Laminar and turbulent flows	Comparison and development of relationships for friction factors	Friction factor depends on the flow behavior index and yield stress.
54/1991	–Sodium CMC solutions –Two phase tube flow	Modeling two phase, non-Newtonian flow	Drag forces of suspended particles and N-N fluids.
55/1993	–Newtonian and non-Newtonian materials –Mixing fluids	Effect of rheological properties on power consumption	Elasticity of fluid materials increased the power.
56/1994	–Sodium CMC solutions –Horizontal pipe	Critical Reynolds number for pseudoplastic fluids	An equation for critical Reynolds number as a function of low index.
57/1994	–Non-Newtonian fluid –Two-phase tube flow	Influence of upstream and downstream on the drag force	An equation was developed to compute the drag correction factor for Stokes's equation.
58/1995	–H-B fluids –Theoretical approach	Develop expressions to estimate the kinetic energy correction factor	Two simple and useful equations were developed.
59/1996	–Wheat flour with low moisture content –Twin-screw extruder	Effect of rheological properties on die design.	The extrudate performance was related to the flow parameters of the dough.
60/1997	–Newtonian and non-Newtonian fluids –Ducts of complex cross-sectional shape	Friction curves for laminar and turbulent regimes Re: 10^{-2} to 10^5	Single friction curve for all types of flow, Newtonian, pseudoplastic and Herschel–Bulkley fluids.

19.3.2 HEAT TRANSFER OPERATIONS

Flow properties are also closely related with those unit operations involving heat transfer phenomena. Cooling, heating, pasteurization, and sterilization are the most common heat transfer operations utilized in food processing, and the main purpose implies flow of food fluids inside of the exchanger.[61] Evaporation is also extensively used in food processing of food liquids, but there are few data on the effect of concentration and heat transfer on rheological properties, or the influence of flow properties on evaporation phenomena, due to very complex flow patterns developed during this unit operation.

Since the flow profile controls mixing and thermal-time effects in the heat equipment, it is essential to know how rheological properties influence the heat transfer mechanisms. Numerous empirical correlations have been developed for the heat transfer of Newtonian fluids, but the existing correlations for non-Newtonian foods are scarce.

Peeples[62,63] established the constant values for the forced convection, heating, and cooling of fluid milk products; this was accomplished by inclusion of the Reynolds number and parameters related to product composition. In a most recent study, Dodeja et al.[64] obtained a correlation to express the heat transfer coefficient of concentrated milk (19 to 70% of solids content) in a thin-film scraped-surface heat exchanger, generating the following equation:

$$Nu = 6615.06 GRe^{0.1331}\ GPr^{0.0764}\left[\frac{\Delta T}{T_s}\right]^{0.2843} \tag{19.4}$$

where Nu = Nusselt number

GRe = generalized Reynolds number
GPr = generalized Prandtl number
ΔT = temperature difference
T_s = temperature of condensing steam

Fortunately, the number of papers related to heat transfer coefficients and rheological properties has increased.[65–69] The proposed empirical equations express the Nusselt number as a function of the generalized Reynolds and generalized Prandtl numbers, including in both of them the flow behavior index and the consistency coefficient. For instance, Alhamdan and Sastry[66] proposed empirical correlations for heating and cooling of aqueous solutions of sodium carboxymethylcellulose and an irregular shaped particle. Chandarana et al.[67] studied a similar system with a starch solution. Bhamidipati and Singh[69] also determined the fluid-to-particle convective heat transfer coefficient and evaluated magnitudes in the range of 108.66 to 195.58 W/m²°F for carboxymethylcellulose at different concentrations.

In relation to thermal processing of non-Newtonian fluids, Palmer and Jones[70] reported a study for the prediction of holding times in continuous thermal processing of power-law fluids. They generated a plot of the velocity ratio in laminar and turbulent flow as a function of the generalized Reynolds number, for different values of the flow index (0.20–2.0). The holding time can then be evaluated as the length over the maximum velocity, the last being obtained from the velocity ratio. More recently, Sandeep et al.[71] and Moyano et al.[72] obtained an experimental equation to compute the residence time of non-Newtonian suspensions and fruit pulp, respectively, including the rheological properties in the following proposed equations:

$$t_{mean} = t_{min} 1.004 Re_p^{0.293-0.288/n} PC^{0.044} n^{0.091} \tag{19.5}$$

$$t_{min} = t_{mean} 0.698 GRe^{-0.26} \tag{19.6}$$

where t_{mean} = mean residence time
t_{min} = minimum residence time
Re_p = particle Reynolds number
n = flow behavior index
PC = particle concentration
GRe = generalized Reynolds number

For the evaporation process, several studies have been conducted to determine the influence of rheological properties on evaporator performance. Chen et al.[73] developed an expression for the heat transfer coefficient in a rotary steam-coil vacuum evaporator, for concentration of tomato paste, involving the consistency of the fluid as apparent viscosity. Stankiewicz and Rao[74] established a correlation for the heat transfer of sugar solutions in a thin-film wiped-surface evaporator. Similarly, they utilized the apparent viscosity as part of the equation. Bouman et al.[75] did the same for falling films evaporators in the dairy industry. Table 19.2 includes relevant studies to emphasize the importance of rheological properties in food process operations based on heat transfer.

There is more information related to the concentration process, which is widely utilized in the food industry for production of fruit juices, evaporated milk, and vegetable purees. Many studies have focused on the effect of concentration and temperature on rheological properties.[81–93] Most of these studies have incorporated solids content, temperature, or both as part of the equations for the rheological parameters. The relationships express the flow behavior index, consistency coeffi-

TABLE 19.2
Rheological Studies Related to Heat Transport in Food Process Operations

Ref./year	Material/experimental	Purpose/hypothesis	Important remarks
76/1979	–Continuous sterilization –Bingham plastic fluids	Modeling continuous sterilization for a non-Newtonian fluid	The effect of *T* over the rheological properties is necessary for a good sterilization process.
74/1988	–Thin film evaporation –Water and sugar solutions	Simulation of fruit juice evaporation	Evaporation regimes were related to flow properties.
77/1989	–Newtonian fluids –Numerical applications	Modeling of heat and mass transfer in a falling film	Pseudo-stationary evaporation was related to Reynolds number.
78/1989	–Double tube heat exchanger –Guar gum and CMC solutions	Predicting heat exchange during laminar flow	Correlations were developed for a non-Newtonian fluid.
66/1990	–Model fluid system –Heating/cooling	Measurement of free convective heat transfer coeff. for particle/fluid	*h* was higher for heating and lower with increasing viscosity.
67/1990	–Starch solutions and water –UHT process	Evaluations of the particle/fluid interface convective heat transfer coefficient	*h* for particles heated in *N* fluid were 20% higher than in *NN*.
79/1993	–Whey protein solution –Tubular heat exchanger	Effect of viscosity on whey protein fouling	Fouling from whey was related to Reynolds number.
69/1995	–Particle in CMC sols. –Aseptic treatment	Determination of fluid convective heat transfer coefficient	Fluid viscosity significantly affected *h*.
80/1994	–Water and starch suspensions –Particulate flow	Calculate incipient fluid velocity for particulate flow in holding tubes	Incipient velocity was affected by porosity, density, and viscosity.
61/1999	–Non-Newtonian and Newtonian fluids –Scraped surface heat –Numerical simulation	Effect of heat transfer on flow profiles	Figures of velocity profiles for three fluids (*n* = 0.28, 0.77 and 1.0) were obtained.

cient, yield stress, or apparent viscosity as a function of concentration and/or temperature.

19.3.3 Mass Transfer Operations

There are mass transfer operations in which fluid foods are handled; therefore, air and spray drying, fermentation processes, membrane separations, and vacuum drying may be influenced by the rheological behavior of the fluid materials. Other unit operations have less dependency on flow properties, such as extraction, frying, leaching, and osmotic dehydration.

Filková[94] conducted a study of spray drying and concluded that the size distribution of the final dry product is related to the consistency of the sprayed liquid and that the viscosity of the sprayed slurry was necessary to predict the droplet diameter. Later, Weberschinke and Filková[95] obtained the apparent viscosity from the rheological properties to evaluate the particle diameter. Hayashi and Kudo[96] concluded that the particle size of powdered skim milk increased with the viscosity of the concentrate. Recently, Hayashi[97] observed that a viscosity of less than 500 mPa-s must be kept to obtain constant good spraying of soy milk.

In fermentation processes, large quantities of substances are involved; diffusion and convective mass transfer then necessarily occur. In formulating mass transfer coefficients, either gases or solids need to pass through the liquids, showing very different rates. The comprehensive correlation of mass transfer coefficients and interfacial areas involves the rheological properties of the liquid phase. Most of the systems take into account only the viscosity of the continuous phase that, in agitated vessels, is usually part of the Reynolds number.[98] Tucker and Thomas[99] investigated the relationship between biomass concentration, mycelial morphology, and the rheological properties of broths, and they proposed that the rheology of fungal fermentation broths should be related to clump properties rather than to the morphology of the freely dispersed mycelia.

Table 19.3 summarizes some relevant research works related to mass transfer operations in the food industry.

19.3.4 Structural Characteristics and Physical Changes

Fluid and semisolid food materials exhibit flow behavior that is both strain- and rate-of-strain dependent; therefore, food components play an important role in rheological behavior and sensory characteristics. Each component (mainly carbohydrates and proteins) responds differently to industrial processes in which the raw food material is performed to manufacture food products.

The structural features of plant food dispersions and their rheological parameters have been studied and related to physical properties of the fluid. Solids content, particle size distribution of solids, and serum viscosity play an important role in the rheological behavior of plant food dispersions, whereas, in the case of milk and milk products, the physicochemical variables such as solids content, type of protein, degree of denaturation, and presence of fat globules, just to mention a few, are very important.

TABLE 19.3
Rheological Studies Related to Mass Transfer Processes.

Ref./year	Material/experimental	Purpose/hypothesis	Important remarks
100/1976	–Skim milk concentrates –Ultrafiltration	Study the relationship between separation and flow properties	Diffusion was related to viscosity.
101/1977	–Sweet potato puree –Dehydration	Flow characteristics of potato puree as indicators of flake quality	Flow properties were significantly related to mouth feel-sensory descriptors.
94/1980	–Water and CMC solutions –Spray drying	Influence of viscosity on drop size of dried products, *nf*	Comparison between droplet size of N and NN fluids.
95/1982	–Theoretical derivation –Spray drying	Droplet diameter of power law liquid	An equation for drop diameter of non-Newtonian fluids was developed.
102/1989	–Power law fluids –Drum drying –Theoretical approach dryer	Film thickness of drying material for a drum	Thickness of the film depended on velocity ratio of cylinders and flow behavior index.
103/1989	–Roasted peanuts –Drying	Effects of drying conditions on textural properties	The higher *T*, the lower the shear-compression force.
104/1995	–Potato, apple, and carrot –Dehydration	Determination of heat transfer during drying	Coefficients for cylinders and slices by a dimensionless expression.
97/1996	–Soy protein milk –Spray drying	Effect of viscosity on drying of soy protein milk	The viscosity must be controlled to get good atomization and milk quality.

On the other hand, processing variables such as applied stresses, cooking time, concentration, holding time, pasteurization time, pH, previous treatments, rate of heating, salts types, temperature, water/solids ratio, and other variables play a transcendental role on the rheological behavior, depending on each product and its manufacturing process.

Important advances in rheological, structural, and textural characterization have been reached by taking advantage of the recent advances in computer technology, microscopy, and rheometric instrumentation. Thus, this part of food process engineering is very abundant in papers and studies in relation to physical changes and structural characteristics related to rheology. Table 19.4 includes some studies regarding this field.

TABLE 19.4
Rheological Studies Related to Structural Characteristics of Foods.

Ref./year	Material/experimental	Purpose/hypothesis	Important remarks
105/1981	–Egg custard –Mayonnaise	Characterizing of stress decay due to structural changes	Steady shear provided information about structure.
106/1983	–Ketchup, butter, margarine, cream, cheese, and peanut butter	Relationship between viscoelastic properties of food materials.	Viscosity and normal stress followed a power-law behavior.
107/1984	–Coagulating milk –Dynamic tests	Changes of viscoelastic properties	Dynamic techniques gave information on milk gel.
108/1987	–Food gels –Thermal gelation of proteins	Rheological changes during gelation phenomena	Rheological and textural methods to follow the gelation of proteins.
109/1990	–Processed cheese analogs –Sensorial tests	Relation between structure, rheology, and sensory texture	Stress and work were related to sensory and structure characteristics.
110/1993	–Whey protein concentrates –Thermal gelation –Dynamic tests	Study of gel structure formation	Higher protein concentrations produced higher storage modulus.
111/1993	–Whey protein concentrates –Dynamic tests	Relation between molecular and rheological properties	The rheology of WPC changed from time-independent to time-dependent shear thinning.
112/1994	–β-lactoglobulins A and B –Thermal gelation/denaturation	Following of gelation process by a dynamic rheological technique	Increasing protein conc. increased the storage modulus being A >> B.
113/1995	–Concentrated skim milk –Membrane concentration	Gelation related to viscoelastic behavior	G' and G'' were related to the gelation temperature.
114/1996	–Surimi-like material from beef and pork	Examine the functional properties of surimi	Gel hardness of samples affected by protein and cooking temperature.
115/1999	–Dynamic tests –Wheat dough –Microscopy studies	Mixing parameters affect microscopy and rheology	Microscopy helped to interpret rheometric data.

19.4 FINAL REMARKS

The role of the flow properties of materials on different food process operations and those related to physical changes has been emphasized. All unit operations involving food liquids as part of the performance will have a more or less strong influence on the rheological properties.

Important progress has been made in characterizing the rheological behavior and structural features of food products, but this is not the case for the rheological influence on food process engineering. However, the use of rheometers and application of rheological models for many food fluids is quite generalized; there are many food materials that still have not been rheologically characterized.

Although rheological and engineering data for food process operations are available, and there are more studies focused on this field, additional research is needed. Studies based on advanced instrumentation, computer technology, digital image processing, microscopy techniques, numerical analysis, and textural measuring devices, among others, will provide a better understanding and modeling of the relationships between the rheological behavior and unit food process operations.

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