FOOD SUSPENSIONS

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Summary

This paper reviews the rheological behavior of food suspensions for colloidal and coarse particles. The main models and factors of non-food suspension rheology are listed. For coarse suspensions, the importance of flow through pipes is also summarized, including predictions of pressure drops and relative particle-fluid velocities. Various techniques are presented for the shear rheometry of coarse suspensions.

1. Introduction

Knowledge of the rheological behavior of suspensions processed in the food industry is particularly important in a number of practical situations:

- Calculation of pressure drops per unit length of pipe for determining the pumping requirements before a canning or packaging process.
- Calculation of the fastest particle velocity (minimum holding time) in aseptic processing for estimating the degree of lethality achieved, i.e., sterilization value.
- Evaluation of apparent shear viscosity and prediction of power consumption in mixing operations.
- Manufacture of products with uniform solid-fluid ratios in the packaging process.

Suspensions are defined as heterogeneous or homogeneous material, in which rigid or deformable particles (disperse system) are mixed with a liquid (dispersion medium). This applies to particle sizes ranging from colloidal (0.001-1μm) to coarse (0.1-10 mm). Due to similarities between the rheological behavior of emulsions (deformable particles of liquid in liquid medium) (see *Food Emulsions*), foams (gas in liquid), and colloidal suspensions, study of these is frequently approached simultaneously. The size limit of colloidal suspensions is not rigid, and in some cases, a larger particle size is present, as in some slurries. Moreover, it is not necessary for all three dimensions to be below a micrometer, since colloidal behavior is observed in systems containing fibers, where only two dimensions are in the colloidal range.

Many foods are colloidal suspensions in which the continuous phase is an aqueous solution. Others may contain coarse particles that are also in a colloidal suspension, a non-Newtonian carrier fluid. Coarse suspensions are usually considered liquid/particulate mixtures and are frequently associated with hydraulic transport. This approach is summarized later.

According to the general physical properties of commercial food suspensions, they can be classified into five groups (Table 1). Most will generally exhibit viscous laminar flow in pumping processes, due to their relatively high apparent shear viscosity (> 0.10 Pa s).

GROUP	CHARACTERISTICS	TYPICAL FOODS
I	Diluted Colloidal suspensions	*Fruit juices, milk*
II	Medium Colloidal suspensions	Pulpy fruit products: purees, sauces
III	Concentrated colloidal suspensions (slurries)	Starch pastes Vegetable pastes
IV	Coarse particles in thin liquids	Vegetable soups Fruits in syrups
V	Coarse particles in viscous liquids	Dressings as mustard with seeds Mexican sauces with seeds Cream style soups Pasta products in sauces Meat in sauces: chicken ragout, meat balls Yogurts with fruits Fruit preserves with seeds.

Table 1: Classifications and examples of food suspensions

In this article, the principal predictive equations and factors influencing the rheological properties of suspensions are summarized, based on the belief that the rheology of non-food suspensions can be used to explain some rheological phenomena present in food suspensions. These studies could help elucidate the rheological behavior of such complex systems, and allow extrapolation to other cases.

2. Rheological Behavior

Food suspensions are complex systems that exhibit a wide range of rheological behavior, as in Newtonian in diluted materials and non-Newtonian in concentrated suspensions (i.e., shear-thinning, shear-thickening, thixotropic, antithixotropic or viscoelastic) (see *Newtonian and Non-Newtonian flow*).

Most food suspension studies are conducted on steady shear flow. Sometimes during the testing, two or more Newtonian and non-Newtonian behaviors can be observed in one suspension at a constant concentration, depending on the range of shear rate studied. Thixotropic and antithixotropic behavior leads to studies on non-steady flow. To evaluate the viscoelastic behavior of food suspensions, a small number of studies have been reported using static or dynamic methods (oscillatory shear) or by measuring the normal stress. In the shear-thinning behavior region of some food suspensions, it was difficult to reach the first Newtonian plateau, due to inaccessibly high values and their measurement, or due to limitations of the rheometer used. In such cases, low shear rate behavior is often described by an apparent yield stress $\left(\sigma_0\right)$, defined as the minimum stress under which flow occurs (see *Newtonian and Non-Newtonian Flow*). The suspension is then reported as a plastic fluid. This concept has been questioned, but has been widely used for engineering design.

Empirical and theoretical models are proposed to describe the rheological behavior of suspensions, as in the Ostwald-de Waele model (known as power-law model), and in the Cross, Ellis, and Carreau models for shear-thinning behavior. The Hershel-Bulkley, Bingham, and Casson models have been proposed for plastic fluids, and the Chaffey model has been used to describe shear-thickening behavior. In food suspensions, the Casson, Herschel-Bulkley, and power-law models have been extensively utilized to describe the time independent shear flow. The kinetic parameter of the Weltman model has been applied to describe the thixotropic behavior of purees. The structural and kinetic model proposed by Tiu and Boger was also used for thixotropic products. The power-law model has been applied to the rheological characterization of time-dependent food suspensions under equilibrium conditions. Some of these behaviors and the models reported for the rheological characterization of food suspensions are summarized in Table 2 (see *Newtonian and Non-Newtonian Flow*, and *Rheological Constitutive Equations*).

PRODUCT	RHEOLOGICAL BEHAVIOR	MODEL
Apple sauces	Plastic	Casson
Apricot purees	Plastic	Herschel-Bulkley

		Casson
Apricot (starch thickened)	Thixotropic	Tiu and Boger
Guava purees	Shear-thinning	Power-law
Peach dietary fiber	Shear-thinning	Power-law
Peach jams	Thixotropic	Weltman
Rice suspensions	Plastic	Herschel-Bulkley Casson
Starch pastes	Shear-thinning Thixotropic Viscoelastic	Power-law
Strawberry jams	Thixotropic	Weltman
Tomato purees	Shear-thinning	Power-law
Tomato sauce (with particulates)	Shear-thinning	Power-law
Tomato concentrates	Shear-thinning	Power-law

Table 2. Rheological behavior of selected food suspensions.

Several studies concerning the rheological behavior of plant food suspensions with colloidal particles, as in juices, purees, and sauces, have been reviewed. Rheological parameters, such as the consistency index (m), apparent viscosity evaluated at a defined shear rate (η_a), apparent yield stress (σ_0), and infinite shear viscosity (η_∞), have been recognized as important product properties for food processing and quality control. These parameters are related in a power-type relationship to concentration (c), ^{o}Bx, or pulp concentration, as follows:

$$\eta_a = ac^b \tag{1}$$

where a and b are empirical constants. In fruit products such as pulps, purees, sauces, concentrates, and dietary fibers, exponent (b) ranged from 2.1 to 3.9, valid only in a limited concentration range.

To account for the temperature effect on suspension, the Arrhenius type equation has been widely used, relating the activation energies of flow:

$$\eta_a = \eta_1 \exp\left(\frac{Ea}{RT}\right) \tag{2}$$

where η_1 is a constant (Pa s), T is the absolute temperature (^{o}K), Ea is the activation energy of flow (kcal mol^{-1}), and R is the gas constant. In rheological studies of fruit sauces and fruit concentrates, Ea ranges from 1.9 to 6 kcal mol^{-1}. It has been observed that Ea increases with sugar content and decreases with pulp content. A large number of power-law parameter values and a more modest number of studies regarding apparent yield stress can be found in the literature. Few studies including large particles have been reported.

Before discussing the principal factors affecting the rheological properties of a suspension and the main equations proposed for rheological prediction, it is important to discuss some of the main forces acting on particles, the disturbing effects caused by fluid flow, and proposed techniques for their measurement.

3. Forces Acting on Particles

The main forces acting on particles follow.

- ***Colloidal forces***:

These originate from interactions between particles in the form of electrostatic charges, and entropic repulsion of polymeric or surfactant material present on particle surfaces. These forces are controlled by properties of the fluid, such as polarizability, involving an overall repulsion or attraction between particles, which means they remain separate. If the net result of all the forces is an attraction, the particles tend to flocculate. It has been explained that the primary electroviscous effect comes from the electrostatic contribution of the charged colloidal particles to the viscosity of the dispersed medium. The secondary electroviscous effect is due to the existence of repulsion effects when the particles approach each other and when an additional dissipative effect (increase in viscosity) appears. The tertiary electroviscous effect is present in colloids owing to particle shape changes associated with modification of their charges by ionization in neutral salts.

- ***Brownian forces***:

These forces ensure that the particles are in constant movement and that any description regarding their spatial distribution is time averaged. For particles of all shapes, thermal randomization influences the form of radial distribution function. These forces are important in particle sizes below a micrometer.

- ***Viscous or hydrodynamic forces***:

Viscous forces are proportional to the local velocity difference between the particle and the surrounding fluid. These forces act on the surfaces of particles or aggregates of particles.

In any multiphase liquid, stability is a main concern, which is altered during the flow of suspensions. Some effects due to various phenomena follow:

- ***Phase separation due to gravitational force***:

Spherical particles larger than about a micrometer tend to settle under gravity, unless the particle density is comparable to that of the suspending medium or the suspending medium is very viscous. Also, small particles are maintained in suspension through

Brownian motion. However, this agitation promotes particle collisions, which often lead to aggregation, followed by gravitational settling or creaming (ascending) of the particle clumps.

- ***Migration***:

Particle migration can be induced by stress or viscosity gradients causing diffusion of particles. Spherical particles may also migrate across a streamline in a prolonged shearing flow. Existence of a velocity gradient can also induce rotation of particles at low fluid viscosity, followed by an increase in suspension viscosity.

- ***Inertial effects****:*

When the particle Reynolds number $\left(\mathrm{Re}_p\right)$ becomes large, inertia can alter the velocity flow around the sphere, causing deviation in viscosity measurements.

- ***Slippage at the wall***:

Forces that occur during shearing can cause the particles to move away from the wall, leaving a liquid rich layer. The phenomena can be minimized using roughened surfaces.

- ***Wall effects***:

Suspended particles must be smaller than the viscometer gap. Particle wall effects are usually small if the particle size to gap ratio is smaller than 0.1 for diluted solutions, but for concentrated solutions, the wall effects can be important for extremely small particles.

The following relationships help to determine if some of these phenomena are present in the rheological characterization of suspensions:

- ***Gravitational settling***:

In general, as the sphere radius decreases, the effects of settling and migration become smaller. From the Stokes law, the time required for a sphere of radius (a) to migrate 10 percent of the rheometer gap (h) under the influence of gravity (g), acting perpendicular to the gap, is

$$t_{0.1h} = \frac{0.45\eta_l h}{\left|\rho_p - \rho_l\right| a^2 g} \tag{3}$$

where η_l is the liquid viscosity and ρ_p and ρ_l are the density of the particle and liquid, respectively. For cone-plates and plate-plates, h is lower than 3 mm, whereas for concentric cylinders, h is $\cong$ 50 mm, since gravity acts parallel to the gap.

Another criterion to predict sedimentation is if the ratio of gravitational forces to Brownian forces is less than unity, at which point, sedimentation does not occur:

$$\frac{a^4 \left|\rho_p - \rho_l\right| g}{k_B T} < 1 \tag{4}$$

where T is the absolute temperature and k_B is the Boltzmann's constant, $\mathrm{k_B T} \approx 4\mathrm{x}10^{-14}$ erg at room temperature.

- ***Inertia***:

For the neglect of inertia, a criterion is

$$\mathrm{Re_p} = \frac{\dot{\gamma}\rho_1 \mathrm{a}^2}{\eta_1} << 1 \tag{5}$$

where Re_p is a Reynolds number based on the particle radius. Particle inertia can occur for >10 μm particles in a liquid of low viscosity (η_1 ~ 0.001 Pa s), since Re_p exceeds 0.1 even at very low shear rates $\left(\dot{\gamma} = 10^{-3}\, s^{-1}\right)$.

- ***Migration inward***:

The stress field around a sphere can interact with the wall, causing the sphere to migrate inwards. To neglect this kind of migration, the following applies:

$$\frac{\rho_p h \dot{\gamma} a^4}{k_B T} < 0.1 \text{ for concentric cylinder} \tag{6}$$

or <0.01 for plane Poiseuille flow and tube flow, where h is the narrow gap of the flow.

- The ***Particle Brownian diffusivity*** (translation and rotation, respectively) in dilute solutions is defined by

$$D_{BT} = \frac{k_B T}{6\pi\eta_l a}; D_{BR} = \frac{k_B T}{8\pi\eta_l a^3} \tag{7}$$

And the diffusion time t_D for a particle to diffuse a distance equal to its radius a is

$$t_{BD} \approx \frac{a^2}{D_{BT}} \approx \frac{1}{D_{BR}} \tag{8}$$

- ***Orientation distribution*** is determined by the balance of hydrodynamic forces and rotary Brownian motion. Hydrodynamic forces are proportional to the viscosity of the medium and tend to align the major axis with the flow, while Brownian motion tends to randomize the orientation. The importance of each is expressed in terms of the Peclet number $\left(Pe = \dot{\gamma} t_{BD}\right)$ for shear flow (a dimensionless shear rate), and is defined as

$$Pe = \frac{\eta_l \dot{\gamma} a^3}{k_B T} \tag{9}$$

$Pe = 0$ Brownian motion randomizes orientation.
$Pe \to \infty$ particles will orient with the flow.

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Biographical Sketch

Laura Patricia Martinez-Padilla was born in 1959 in Mexico City. She received her early education in Food Engineering at the National Autonomous University of Mexico (UNAM), Mexico, before moving to the Institut National Polytechnique de Lorraine in France where she obtained a Food Science Diploma and finished her Doctorate in Biotechnology and Food Industries in 1988.She was visiting Faculty in the Biological Systems Engineering department at Washington State University (USA), The Centre National du Machinisme Agricole, du Génie Rural, des Eaux et des Forêts, Division de Génie et procédés frigorifiques (France) and The Laboratoire Biorhéologie–Hydrodynamique-Physico-chimique at the Université Paris VII Denis Diderot (France) for her sabbatical year. Since 1980, she has been in the Department of Engineering and Technology at the UNAM as part of the Food Engineering faculty. Her interests and work have centered on the physical properties of food materials and fluid mechanics. In 1989, she started a Laboratory of Rheology and Functional Properties of Foods. She is the author of more than fifteen international publications and has attended more than 30 conferences and courses on the topic of Food Rheology. She has received four research scholarships from different Mexican sponsors, and was honored as the best Food Engineering student in 1981. In 1998, she received The Young Researcher award in the area of Technological Innovation and Industry Design at the UNAM.