# Rheology in Feed Production

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## ABSTRACT

Information regarding rheology in feed production is very rare, but considerations of flow and deformation of matter are important as they influence process efficiency and product quality. This article describes some of the main rheological concerns and challenges that need to be faced in order to improve the feed industry.

## INTRODUCTION

Industrial production of feed is relatively new and much of their effectiveness to supply the food chain depends on understanding and improving the parts of the process where rheology is involved, thus all parts where flow and deformation are present.

Rheological properties are important for quality control, storage, process stability measurements, prediction and measurements of texture, learning about the molecular conformational changes in the materials, and flavour release[1]. The phase states (e.g. crystalline, rubbery, melted, etc.) are rheological properties that affect processing, quality, and stability[2]. Rheological data is necessary to design continuous-flow processes, select and size pumps and other fluid moving machinery and to evaluate heating rates during engineering operations[1, 3, 4] including feed manufacturing processes[5].

The physical characteristics of elaborated foods for animals can vary significantly (from pet soups to dry feed pellets). This article will only focus on the manufacture of dry feed pellets and some of the unit operations where rheology is a key issue.

The rheological concerns upon pneumatic conveying and measurements of pellet quality will not be addressed in this article, but can partly be found in the literature[6-8]. A block diagram in Fig. 1 shows the main issues that will be included in this article.

### Raw Materials

The rheological properties of raw materials provide relevant information about their structure, their behaviour during processing, and their end-use properties[1, 4, 5, 9, 10].

Cereals are used as raw materials for feed; their rheological characteristics can vary according to their genotype, harvesting, processing and storage conditions[10-12]. The raw materials from animal origin also present rheological differences due to breeding differences, processing conditions and storage. Thus, rheological behaviours of raw materials during different processing intervals are rarely equal. Components like starch, proteins, water, sugars and lipids can interact and lead to more or less organized structures influencing the rheological behaviour. A feed mixture can be considered as a multiphase; rheologically complex material.

Today the selection of raw materials and recipes is done by computer software focusing on prices and nutritional values, but the physical composition of the different raw materials can greatly affect the process

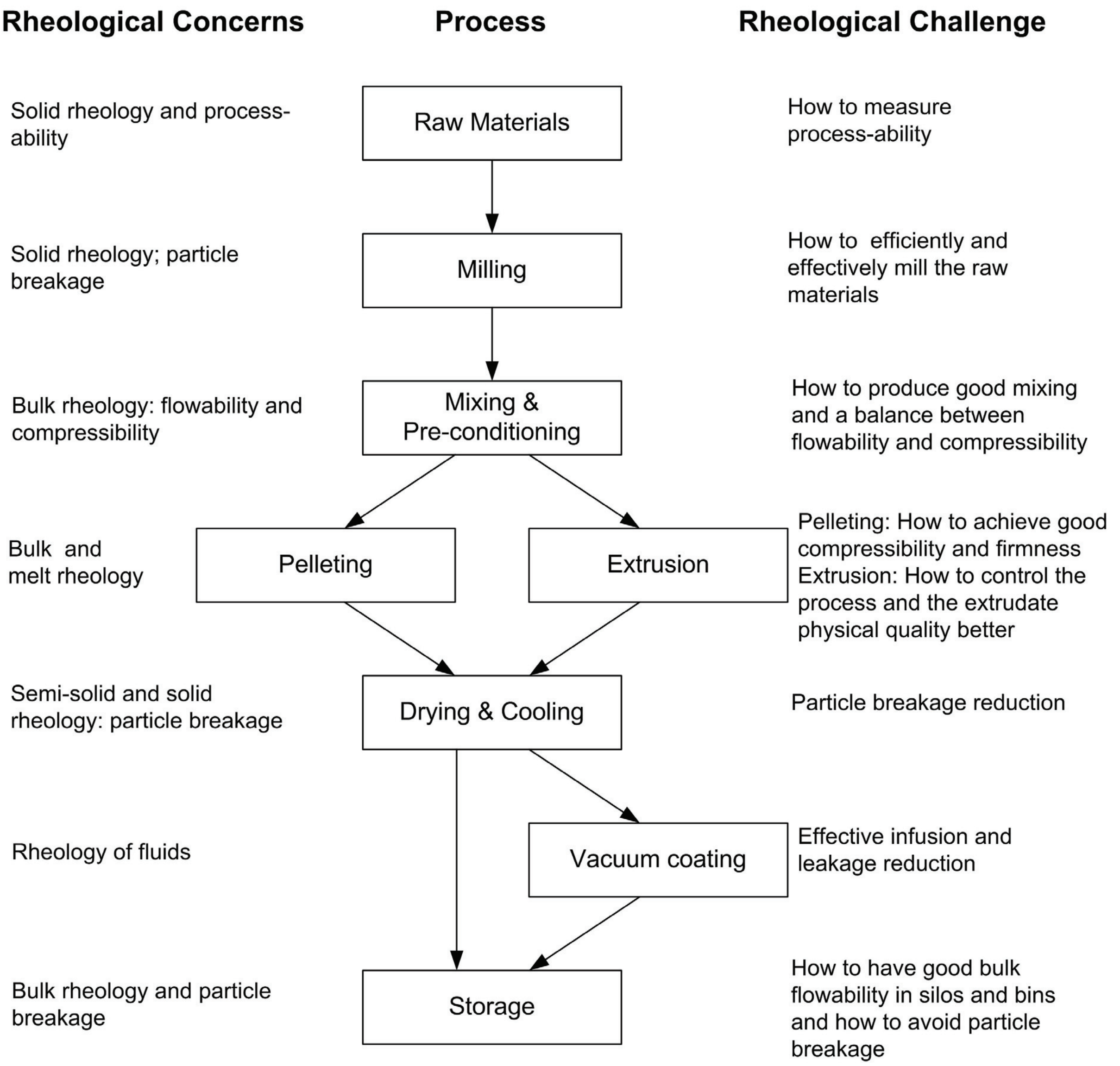


Figure 1. Block diagram summarizing the main rheological concerns and challenges.

performance, on extreme cases, some recipes are simply not possible to be mechanically processed (i.e. the feed cannot flow through the die during pelleting, ref. pellet-ability), thus rheological considerations are required to determine process-ability[13].

According to an unpublished survey, conducted in Norway in 2005, determinations of process-ability are a great need among the feed industry and research institutions when creating new recipes, but there is no common rheological instrument assessing process-ability. Efforts have been made to develop a rheometer[5, 14] that mix, kneads, shears and forces powders (e.g. recipes or raw materials) to flow through a die.

Measurement of material resistance to flow can then be used as an indication of process-ability[13].

## PRE-FORMING OPERATIONS

### Milling

Rheology in milling is important to understand and control the mechanisms of particle breakage better, and for better selection of milling equipment.

The feed industry uses mainly two types of milling units; roller and hammer mills. The types of forces used for grinding in roller mills are compressive, impact and shear. In hammer mills the main forces are due to impact and in lower level attrition forces[15].

Deformation and breakage of grains under the influence of applied stresses is important in milling. The milling mechanisms can be explained in rheological terms. In roller mills, when the distance between rollers is smaller than the grain size and no breakage is achieved, the grains experience an elastic deformation (they returns to their original shape when the force is removed). Now, if the distance between rollers is small enough to produce breakage, the stress exceeds the elastic limit, the material undergoes permanent (inelastic) deformation until it reaches the yield point when it begins to flow (i.e. region of ductility) under the action of the applied stress until it finally breaks[15, 16].

Knowledge of the particular structure of grains can indicate the type of force most likely to be used in performing the size reduction. If the material is brittle or has a crystalline structure, fracture may occur easily along defined planes during milling, with larger particles fracturing more easily than smaller ones. In these cases, crushing using compressive forces would be recommended. When few cleavage planes are present, and new crack tips have to be formed, impact and shear forces may be more advisable (e.g. hammer mill). Many grains have fibrous structures, so they are not easily reduced by compression or impact. In such cases, shredding may bring the force needed to perform the desired size reduction[15].

### Mixing and Pre-conditioning

Knowledge of the rheological properties of ingredients is important to ensure good flow conditions during mixing operations. In pre-conditioning, how plasticization affects flowability and compressibility is important for the forming operations.

Since mixing and conditioning involve the flow of powders, mixing mechanisms can be affected by the same rheological properties that affect flow: mechanical interlocking, surface attraction, plastic welding (from high pressures between small contact areas), electrostatic attraction, moisture and temperature fluctuations. Powder flow properties can simplify blender selection by allowing the prediction of the behavior of materials of specific composition in different types of mixers[15]. Shear mixing is very common and is induced by the momentum exchange of powder particles having different velocities. Shear mixing is developed by the formation of slipping planes in the bulk material; the originally coherent particle groups are gradually broken along these planes. The velocity distribution develops around the agitating impeller and the vessel walls due to compression and extension of bulk powders[15].

A mixing between feed powders, liquid-stuffs and steam is required for the forming operations. During mixing-conditioning, dough development begins as raw materials are combined and macromolecules are hydrated. Water acts as a plasticizer for cereal based materials[17]. The plasticizing effect on rheology when increasing moisture content at constant temperature are similar to the effect of increasing temperature at constant moisture content[18].

The conditioned mixture must acquire good flowability and compressibility for the forming operations; they will be explained in the forming sections.

## FORMING OPERATIONS

Feed pellets can be formed by two different processes; extrusion and pelleting. Extrusion is normally operated as extrusion cooking and product temperatures are higher than in pelleting processes.

### Pelleting

Pelleting can be regarded as a kneading, compressing and forming process where rheological transformations in the material take place. Rheological properties (e.g. compressibility, resistance to flow, etc) influence pelleting performance and product quality.

Good flowability of the conditioned feed in pelleting is important to fill regularly the die section where the rollers are located. At the same time, good compressibility of the feed mixture is important for the compaction and shaping in the pellet press die. This in general is one of the continuous challenges for plant operators because the higher the compressibility the poorer the flowability[15].

The feed material as it is kneaded, heated[19] and compressed by the rollers and die, possibly changes its phase state, which should be between the solid glassy state and the melted state, probably in a rubbery or crystalline state, having a semi-solid behaviour (i.e. viscoelastic). Thus, the material is able to deform and flow when stresses are applied towards the die. Unfortunately, because of equipment design, the rheological properties of the feed during pelleting are difficult to measure, and thus, to a large extent pelleting remains a black box.

Measurements of rheological properties could be approximated in a lab by using pressure–density relationship for a given powder or feed mixture, a set of compression cells (usually a piston in a cylinder) can be used. The tested powder can be poured into the cylinder and compressed with the piston attached to the crosshead of, for example, a TA-XT2 Texture Analyzer (Stable Micro Systems, England) or Instron Universal Testing Machine. Normally, the instrument will record a force–distance relationship during a compression test[15].

A measurement of the resistance to flow of conditioned feed could be done continuously during processing to indicate pellet-ability. This by using the online process rheometer developed by Salas-Bringas et al.[5, 14], which kneads, shears and compresses the powders to finally force them to flow through a die. Today this apparatus is at a prototype level. Measurements of the material resistance to flow (e.g. bulk viscosity) are important as they influence the confinement pressure in the die, the hold time in the press, throughputs and power consumption.

The friction within the feed mixture determines the resistance to flow. Friction between powder and die walls is also important, as it is one of the main contributors to density gradients in powder compacts[20].

In general, there are two important phenomena that may affect the performance of the feed compaction: compressed air between particles and elastic springback in the compacted material. Both can cause cracking and weakening which, in turn, may lead to destruction of the agglomerated feed. The effect of these two phenomena could be reduced if the maximum pressure is maintained for some time, known as dwell time, prior to its release[15]. Unfortunately, this type of control is difficult to be achieved in a pellet press today. When die compaction finish, during press release, a relaxed elastic recovery should be expected, however an important part of it should be resisted by the presence of friction between the particles. Friction is present due to the existence of residual stresses within the compact that have a component that is normal to the die surface.

Qualitatively speaking for a given recipe, when the pelleting die pressure is medium or low, relatively uniform agglomerates can be obtained. Under these conditions, the porosity of the material is changed, but no big change in particle size or its shape should occur. The agglomeration and shaping are due to the pressure forcing the material through the die holes, as well as by frictional forces. A higher pelleting pressure will likely increase agglomeration by increasing the degree of densification, resulting in lower product porosity. Typically, the products from high pressure agglomeration feature high strength immediately after discharge from the equipment[15, 16].

Rheological behavior of compressible powders is more complex to deal with than that of incompressible solids and thus, to achieve good pelleting, new and more sophisticated production planning and process control are required, that includes knowledge of how the mixture responds to applied stresses during compaction and pellet release, keeping in mind crack prevention.

Computer modeling of powder die compaction has a reputation of being limited to density predictions on simple shapes and has been slow to perform, however, today modern PCs are fast and capable. Providing modeling input data with sufficient accuracy (e.g. powder elasticity and powder plastic data), these software programs can deliver accurate quantitative information on stresses and press functions that previously could only be estimated[21].

As soon as the pellet is formed, the rheology of particle breakage begins to be important again.

Extrusion

Extrusion combines mixing, kneading, and forming into one unit operation. Extruded feed are produced through a broad range of operating parameters forming a large variety of structures and texture[22].

The bulk rheology of the conditioned feed is important in the feed hopper region and first part of feeding zone (e.g. flowability and compressibility). The rheological properties of the melt (e.g. viscosity and viscoelasticity) are important in the plasticating zone, the melt conveying zone, and the die forming region[23].

At the hopper and feeding zone, poor flowability can occur when the bulk density of the conditioned feed is low, resulting in insufficient mass flow rate to supply downstream zones (e.g. plasticating and melt conveying) with enough material. Crammer feeders are used in these cases to provide a steady mass transport from the feed hopper into the extruder barrel[23].

Extruded feed is normally produced by cooking extrusion, using high shear and temperature for short times. This results in many physical and chemical changes in the product including starch gelatinization and protein denaturation[24, 25] which turns into a non-Newtonian, shear-thinning and viscoelastic melt[5, 26, 27].

Various types of organization (e.g. suspension, network and melt) may be encountered under different flow conditions along the extruder[10]. Even within a single screw channel, different viscosities will be present as shear rate depends on position[5, 23].

The extrudate rheology is the foundation of the extruder behaviour[28] which determines process parameters like power consumption, throughputs and the specific mechanical energy (SME) as it affect torque. If properties like melt flow are unknown, the extruder screw configuration and the determination of the process operating conditions becomes a trial and error process at best[23]. Understanding the rheology and momentum transfer in an extruder can optimize product development, processing methods, scale-up, process control, product quality and heat transfer analysis[22, 24].

An example of how a rheological change affects heat transfer and working conditions is given. An increase in the consistency index *K*, leads to an increase in the viscous dissipation of heat. For lower consistencies, viscous dissipation is not large enough for the material temperature to reach barrel temperature, which also underlines the slight influence of thermal conduction. Also an increase in thermal, water, or mechanical sensitivities would lead to the same variations as a drop in *K*. An increase in the flow index leads to an increase in the die pressure and a pressure decrease at the reverse screw entrance. The first is due to the increase of viscosity with flow index and the second is explained by the larger pumping efficiency of screws in the case of fluids having higher flow indices[10].

Viscous shear behaviour of molten feed recipes is only beginning to be understood and studied by few feed researchers.

The rheological history during extrusion is very important to consider. For example, physical and chemical differences can result even when final compositions and temperatures are identical[28]. To monitor these changes, on-line measurements can be performed by attaching a capillary slit die to the extruder[23]; this configuration has been used in the polymer industry for many years[24, 29]. Another way to estimate the rheological properties is by using the “quick and dirty” determination using the die as an in-line rheometer by ignoring the die inlet and outlet effects[25].

A systematic study of the influence of the main rheological features on pressure, energy, and temperature would involve a tedious experimental work. To overcome this difficulty, one might simulate the working conditions of the extruders using theoretical models of heat and mass transfers, which are now available for both single and twin screw corotating extruders. Such models offer the possibility of simulating cases that cannot be experimentally achieved, or of predicting the variations in variables that cannot be easily measured[10].

The modelling equations can be in many forms, but no single master model can represent and explain all situations[22, 28]. The three criteria to select a particular rheological equation are: how well represents the experimental data, how well predicts phenomena controlled by viscosity, and how convenient is to use it[22]. Rheological models mainly focused on the effects of shear rate, temperature, moisture content, time-temperature history, strain story, and starch gelatinization on viscosity[22].

As the extrudate leaves the die, viscosity rapidly increases and the product acquires a porous structure, like foam[30], due to transient heat and vapour transfers, which together with viscoelasticity determines the pore size, thickness, density and texture[10]. In extrusion cooking, the melts cools very rapidly and settles into a solid state. Because the time to reach the solid state is faster than the time required for crystallization, often high-temperature extrusion process, extrudate in a glassy state[18, 30].

There is a general agreement that the rheological properties play an important role in bubble growth[10]. Confusion between expansion and extrudate swell due to the elastic properties of the melt, is sometimes made. The later phenomenon is of interest only when no expansion takes place, i.e., for temperature low enough to avoid water vaporization[10].

Melt fracture is a problem detected by seeing an irregular surface in the extrudate when removing the knife. Melt fracture is produced by die flow instabilities as a consequence of the melt rheology, flow channel geometries and magnitudes of shear stress at the die. Proposed mechanisms to explain this are rheological: (1) critical elastic deformation of the entry zone, (2) critical elastic strain and (3) slip-stick flow in the die[23].

## POST-FORMING OPERATIONS

### Drying and cooling

Drying of feed is normally done using hot air with a relative humidity similar to the ambient, drying can be performed by fluidization or by blowing air though a packed bed of pellets. Drying removes moisture, sets the structure and increases shelf stability[12]. Cooling is commonly done by blowing air at room temperature though a pecked bed of pellets until they apparently reach room temperature.

In both processes, the most challenging rheological characteristic to address is breakage, which can be produced by moisture and temperature gradients inside the product[12]. Temperature gradients in cereal products equilibrate rapidly, so the main cause of stress development and breakage is moisture gradients[12]. Optimization of drying conditions requires knowledge of the effects of variations in raw materials, processing (e.g. mixing, extrusion or pelleting) and product structure. Product behaviour is reflected in the material properties, which influence water mass transfer and stress development.

It is important to understand well the air flow dynamics, heat and mass transfer, and textural changes during drying and cooling to optimize the process. Processing conditions are often tested by trial and error method, which is extremely inefficient if multiple parameters are being changed. Numerical simulations based on mechanistic models can be more efficient method than plant tests[12]. Drying and cooling are numerically simulated using mechanistic mass transfer and stress development models that require material property inputs as functions of temperature and moisture content. Information from such models includes drying rates, drying curves, moisture profiles, shrinkage, and stresses in multiple directions. The models require several material properties, including isotherms, glass transition temperature, storage modulus, diffusion coefficient, Young’s modulus, failure stress, and Poisson’s ratio, as functions of temperature and moisture content[12].

As moisture is removed, the material shrinks and may change from pliable, rubbery state to a brittle, glassy state. This transition inhibits shrinkage, resulting in stress development and potential failure[12]. On the other hand, few stresses and cracks develop if the material remains rubbery during drying, when stiffness is low, so viscous relaxation is possible[12]. After water removal, products retain their characteristic texture in the glassy state, when stiffness is high[12]. If the material is re-hydrated, plasticization can occur, resulting in collapse or loss firmness (Young's modulus decreases)[12].

Besides the rheology of the particle, the flow dynamics in a fluidized bed is also related to damages in the feed (producing attrition or particle wear) due to bulk shear[31]. Fluidized beds are a 2-phase flow system (solid and gas) and its flow dynamics must be well known to be controlled.

Vacuum coating

Vacuum coating is a vacuum infusion process where usually oils are added into dry feed pellets. The process requires adding feed pellets to a sealed mixer. Depressurization of the mixer is the first step (~0.2 bar, abs.) to remove the air, even within the product pores. The liquid coating is then sprayed into the vessel via nozzles whilst the product is blended via paddle mixing. The vacuum is slowly released. The rate of pressure raise is a very important point to control because the external pressure must rise at a rate that is able to sustain the rate of flow of liquids into the pores (depending on oil viscosity). The rate of flow must also not exceed the rate of wetting of the pore inlets. When pressure equals atmospheric conditions, the vessel may be discharged[32].

The rheological phenomena in coating are coalescence, wetting and sagging. Coalescence is the fusion of oil droplets to form a continuous film and depends on the surface tension and viscosity of the oil. Wetting determines the ability of the oil to adhere to a substrate and depends on surface tension. The rate of wetting depends on oil viscosity and the surface roughness of the feed (including pores). Sagging can explain the oil leakage in coated feed, these downward flows occur influenced by gravity and the extent of viscosity[33].

Since in natural oils, viscosity is temperature dependent, infusion could be improved by adding warmed oils, but oil viscosities at room temperature should be high enough to avoid leakage. Extrudate expansion and shrinkage must be well controlled to produce pores small enough to create a high resistance to leakages, but big enough to infuse oil.

Possibly blending oils with innocuous additives to produce a viscoplastic or viscoelastic fluid could finish with leakage problems.

Storage

The main rheological concerns in storage in silos and bins are the ones related to flow, attrition and breakage of particles (both are often included under the term attrition), and the structural stresses in silos or bins.

Various types of flow may occur in silos and bins; mass flow, arching and funnel flow. The first type is desired as the entire volume of particulate solids moves down, but arching and funnel flow are not. In arching, the material consolidates at the bottom of a silo or bin to an extent that can support the material above and stop flow. In funnel flow, the material flows out through a channel; the wall of the channel is being formed by stationary particles in the bulk material (i.e. stagnating region). Cohesiveness, friction and interlocking between particles produce these problems, commonly showing high unconfined yield strength[23].

To guarantee steady and reliable flow, it is crucial to accurately characterize the flow behaviour of particles. The forces involved in their flow are gravity, friction, cohesion (inter-particle attraction), and adhesion (particle-wall attraction). Furthermore, particle surface properties, particle shape and size distribution, and the geometry of the system are factors that affect the flowability of given particles. It is therefore, quite difficult to have a general theory applicable to the flow of all feed particles in all possible conditions that might be developed in practice.

The first requirement is to identify the properties that characterize the flowability of a particular material and to specify procedures for measuring them. The way the shear strength varies with the consolidating stress, and the properties used to identify and quantify such interactions, are commonly known as the failure properties of powder[15].

Attrition tests help to evaluate particle breakage and fines generation by abrasion from flow of a bulk solid (e.g. flow in a silo). With this kind of test, products can be compared regarding their sensitivity to attrition, at different stress conditions. It is important that the stress level of an attrition test can be adjusted to the conditions that simulate where a product is stored or handled. Fines are generated when particles are subjected to stresses, but a static load has to be distinguished from shear deformation (kinematic load). Commonly and not un-expected, more fines are generated by kinematic load (e.g. bulk shear[34]) than by static load at the same stress level[16].

Fig. 1 summarizes the main rheological concerns and challenges presented in this article.

## CONCLUSIONS

Rheology is undoubtedly a major issue in feed production. Knowledge of rheological properties in connection with structural features at different scales (e.g. macromolecular structure, network complexes and macroscopic properties) is absolutely necessary to understand the elementary mechanisms involved in the processes and thus to optimize processing conditions, equipments, and product quality.

As it is shown in this article, rheology is an important aspect that must be considered in almost every single processing step in feed production.

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