# Rheology in Solid Biofuel Production

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## ABSTRACT

Solid biofuel production is at the very beginning and therefore rheological information is not common, but considerations of flow and deformation of matter are important as they influence the manufacturing process and product quality. This article describes some of the main rheological concerns and challenges that need to be faced in order to progress within the solid biofuel production.

## INTRODUCTION

Nowadays solid biofuels is largely dominated by the production of compressed wood powders like sawdust in pelleted form.

The increased demand for world energy leads to a search for all types of fuel sources, and within the most important to take into consideration are the renewable ones. However, many renewable raw materials used for fuel production (e.g. corn to produce ethanol, vegetable oils to produce biodiesel, etc.) are affecting critical areas like food production. For example, the production of ethanol and biodiesel from raw materials, that also can be used as animal or human food, is raising the food prices at worldwide level[1].

Within the alternatives for energy are the solid biofuels. Currently, solid biofuels are not a worldwide source of energy, the most common example of solid biofuels is wood pellets. Wood pellets can be used to replace fossil fuels, both in small scale oil heating systems and for large scale coal combustion plants. Also wood pellets are used to heat houses and buildings. The wood pellet production process is summarized on Fig. 1.

Solid wood pellets are considered a renewable source of energy. Wood pellets have a good energy value (~4.8 kWh/kg, bulk values[2]), however still many countries do not oblige reforestation, which can make the use of wood for energy a matter of discussion. Nevertheless, sawdust and other residues from wood industries are a good renewable source of energy when making wood pellets, and as substitute for fossil fuels[3].

Within the possibilities to increase the energy sources, are the use of renewable organic materials which comes from urban or industrial residues. They do not affect key areas like food prices and forestation. Unfortunately, organic residues from urban and industrial activities are continuously produced. These residues have a caloric value which can be utilized to generate heat or electricity. For an environmental/energy assessment, it is possible to assess the total energy obtained from the solid biofuel considering the energy consumed by a gas separation process to minimize greenhouse gas emissions.

Research is expected to grow in this direction and rheology will play a major role since the process to produce these biofuels is based on compacting processes. The compressibility of different materials is different and therefore when one tries a new raw material, it is likely to obtain a product having a different density to the ones made with previous raw materials, even when compressed at the same pressure. Also it is likely to have a different energy requirement to produce the new compact. Knowledge within compression rheology is thus needed in this field.

Another need for rheology within solid biofuel production is to determine the strength of the solid fuels. For wood pellets, it is required that the new solid biofuels should remain in pelleted form when handled at the production plant until it reaches the combustion chamber.

## PRE-FORMING OPERATIONS

The rheological characteristics of residues from different wood species, urban and industrial activity can vary. Also the rheological properties of wood powders can vary according to the tree genotype, area of harvest and storage conditions[4, 5]. Thus, rheological behaviours of raw materials during processing are likely to challenge the production of solid biofuels.

### Milling

Rheological information from the different raw materials is important since it is important to select the equipment which is going to mill a large variety of raw materials.

Deformation and breakage of solid materials under the influence of applied stresses is important in milling process. The milling mechanisms can be explained in rheological terms. In roller mills, when the distance between rollers is smaller than the raw material size and no breakage is achieved, many raw materials can 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 raw material undergo a 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[6-8].

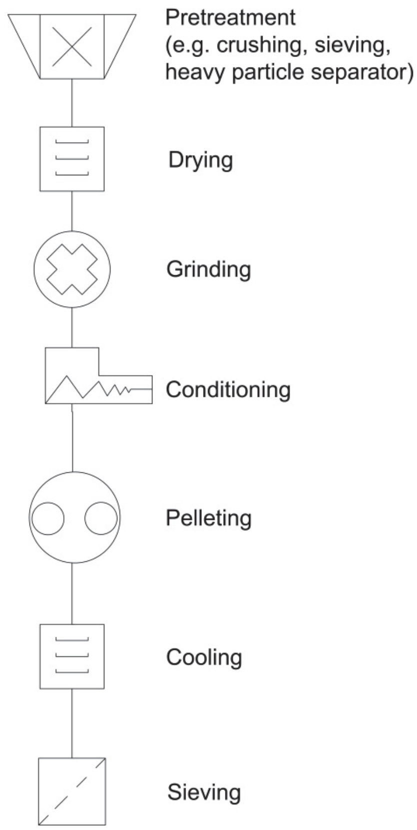


Figure 1. Main steps in wood pelleting process.

Knowledge of the particular structure of the raw material can indicate the type of force most likely to be used in performing the size reduction. If the raw 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 raw materials with organic origin 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[6].

The most common milling equipment in wood pellets production is hammer mill.

## FORMING OPERATIONS

The most common form of solid biofuel today is wood pellets. The forming operation or compaction process is done by pellet presses.

### 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 ground mixture in pelleting is important to fill regularly the die section where the rollers are located. At the same time, good compressibility of the 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 of similar compacting processes like feed pellets. Animal feed pellets as well as the future of solid biofuels face the same problem when using new raw materials continuously. Regarding compressibility and flowability of the mixture is difficult to have a balance because the higher the compressibility the poorer the flowability[6].

For crop residues, they can behave in a similar way as the animal feed materials when they are kneaded, heated[9] and compressed by the rollers and die during pelleting process. Often it is observed changes in the phase state of animal feed mixtures, which should be between the solid glassy state and the melted state, probably in a rubbery or crystalline state, having a semi-solid behaviour (e.g. viscoelastic/ viscoplastic). 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 mixture during pelleting is difficult to measure, and thus, to a large extent pelleting remains a black box[8, 9].

Measurements of rheological properties can 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 ground raw materials can be poured into the cylinder and compressed with the piston attached to the crosshead of, for example, a Texture Analyzer. Normally, the instrument will record a force–distance relationship during a compression test[6]. This type of instrument had been successfully built and used to produce solid biofuels made of wood[5] and animal feed pellets[10, 11].

The friction within the pressed raw materials and towards the die walls 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[12]. Also friction is responsible for the relation pressure - die velocity. Furthermore, Salas-Bringas et al.[4], developed a method that determines the resistance to flow of compacted powders through a stress relaxation test. The results showed a correlation between the minimum force required to initiate die flow with the power consumption given by an industrial pellet press producing solid biofuels made of wood.

In general, there are two important phenomena that may affect the performance of the compaction process: 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[6]. Unfortunately, this type of control is difficult to be achieved in a pellet press today. When die compaction finish, during pressure 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 powder mixture, 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[6-8].

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.

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

## POST-FORMING OPERATIONS

### Cooling

Cooling is commonly done by blowing air at room temperature though a packed bed of pellets.

In both processes, the most challenging rheological characteristic to address is breakage, which can be produced by moisture and temperature gradients inside the product[13]. Optimization of drying conditions requires knowledge of the effects of variations in raw materials, processing (e.g. mixing and 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 cooling to optimize the process. Processing conditions are often tested by trial and error method in most pelleting industries, which is extremely inefficient if multiple parameters are being changed.

As moisture is removed, many materials can shrink and some raw materials can change from pliable, rubbery state to a brittle, glassy state. This transition is known to inhibit shrinkage, resulting in stress development and potential failure[13]. 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[13]. After water removal, products retain their characteristic texture in the glassy state, when stiffness is high[13]. If the material is re-hydrated, plasticization can occur, resulting in collapse or loss firmness (Young's modulus decreases)[13].

### 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[14].

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[6].

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[15]) than by static load at the same stress level[7].

## CONCLUSIONS

Rheology will certainly be a major issue in solid biofuel production. Understanding of rheological properties (compression rheology and shear rheology) in connection with the processing is absolutely necessary to optimize the processing conditions, equipment 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 solid biofuel production.

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