ABSTRACT OF THE PH.D. THESIS

THE COMPRESSION RHEOLOGY AND ENERGETICS OF WOOD PARTICLE SETS AT PELLETING RANGE

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ABSTRACT

This Ph.D. thesis presents the process of high pressure compression of wood chips and dust sets in the context the pelleting spruce (*Picea abies*), oak (*Quercus sp.*) and acacia (*Robinia pseudoacacia*) species. The mechanical properties of high pressure produced pellets depend on many factors. The most important factors are wood species, particle size, moisture content, compression pressure, the speed of compression, the holding time on deformation, the diameter of ram and the temperature of pressing. The dissertation examined the influence of these factors, and then made conclusions. Description of resulting mechanical changes during high pressure compression of wood chips and dust sets (σ-ε relationship) happen by non-linear rheological methods, whereas the wood has non-linear viscoelastic property. Consequently, during the compression process greatly increases the elastic modulus of wood chips and dust set, and the resulted pellet at the end of the process suffers residual deformation. The rates of residual deformation determine the properties of pellet, especially density. The dissertation considers it highly important, examining the impact of influencing factors at compression process of wood chips and dust sets and then the development of new mechanical models based on the received results. In this connection, the extend force and the required length of press channel approximate mechanical modelling has been developed which are related to the relative wall friction. Well as we created a dimensionless criterion equation which is generally characterized (independently wood species) pressure and density changes of wood sets in the function of compression work and press temperature at different pellets diameters and specific particle size range. I also proved with measurement the derived theoretical correlations. The obtained results are useful for practice and contribute greatly to the expanding the theoretical knowledge of wood chips and dust sets.

INTRODUCTION AND OBJECTIVES

Nowadays, in the practice where the pressure increase the 1000 bar (100 MPa) value increasingly spreading the pelleting of certain agricultural substances and materials from wood industry. The examinations of compaction are required for wood pellets, because the pellets should be stable, durable and appropriate density. This means that pellets does not fall apart. The stability is affect over the size distribution of particles the moisture content, achieved density and temperature of compression. The compactions investigations of wood chips and dust sets have a great practical importance in the field of pelleting and briquetting technologies. Result of the compression process the wood sets has smaller volume and the density is increasing. The starting density of the pellets mainly depends on the size distribution of particles as well as strength and density of the particles material. The wood – as a complex structured biomechanical system – behavior does not characterized by some physical constants such as in the case of metals. Mechanical properties are not constant, but depend on a variety of factors.

These factors are the own properties of the wood (eg. growing site, moisture content, density, age, etc.), on the other hand, the behavior from the resistance of the external force. Still rises many questions the resulting from the above that the wood with the various external and internal forces acting on related behavior. That's why the importance of basic research has appreciated. The result of the wood complexity, during the negotiations of mechanics has to make relatively large number of assumptions and the results obtained are valid only in the given conditions. Often have to resort to empirical methods that we could write to the observed phenomena. Whereas purely theoretical considerations are seldom suitable results therefor the experimental investigations are particularly important. It is very important to evaluate the test that we have to accurately record all the characteristics of the material which influence the results (wood species, moisture content, particle size, density, load, etc.). The high-pressure compaction process of wood chips and dust sets related the domestic and foreign researches are incomplete. In order to facilitate the sequential use of pellets – as a renewable energy source – firstly needed a well-designed state support and incentive system, secondly a targeted basic research. We used to determine the influence factors with basic research, which are related to the material and technology of pellet. Addition to the state support system, needed to reduce manufacturing cost of pellets, in order to know the increase the competitiveness of pellets in the energy sector. These are composed of two parts, logistics and technology costs. This dissertation therefore also examined rheology and energetic side of the wood chips and dust sets compactions process and contributed to the benefits of theory and practice.

The main aims of the dissertation intend to utilize the results obtained to the theory and practice. *Practical terms propose* that carry out investigations on the topic at different measurement parameters and find the optimum parameters the context of material properties, as well technological parameters, that these allow reduce the energy consumption of the pellet technology and increase the density and quality of pellets. *Theoretical aspects propose* describing mechanical knowledge in high pressure compaction process of wood chips and dust sets and expand the regularities at the range of pellets.

MATERIAL AND METHODS

Three types of air dry (10-12%) wood species were used for the research: spruce (*Picea abies*), oak (*Quercus sp.*) and acacia (*Robinia pseudoacacia*) wood chips. It was important to know the fraction size of wood chips, because the particle size affects the density of the pellets. The existing wood chips and dust samples were shredding with shredders machine of experimental pelleting system (Type of the pelleting system is NOVA PELLET N MICRO B). Thereafter these were fractionated with electromagnetic sieve shaker device (CISA BA 200N). In the practice the pellet is made by between 0.5-1.5 mm shredded fractions, so the assembled sieve shaker device were: 2.5mm, 1mm, 0.8 mm, 0.5 mm, 0.2 mm, 0.063mm. The weight of each fraction's residual value has been measured after the drizzle with type of KERN PCB 3500-2 digital scale. Based on the results obtained the fraction analysis was found that 95-98% of the fraction is between 0.2-1.5 mm, within it 90% of particle size is between 0.2-1 mm. There is also a significant role of the fraction between 0.2-0.5 mm. Moisture content of the fractions was determined type of Boeck SMO 01 automatic moisture meter. The compression tests were carried out unique designed and constructed rams. The ram's diameters were 6 mm, 8 mm and 16 mm. The measurements which were associated with temperature also were carried out unique designed and constructed temperature control and measurement system.

During the research, the following measurement parameters were applied:

- loading (deformation) speed [$v_{def.}$; mm/min]: 2 mm/min, 10 mm/min, 60 mm/min,
- pushing speed [$v_{kit.}$]: 8 mm/sec,
- compaction pressure [p; bar]: 500-1400 bar (50-140 MPa) and bellow 500 bar,
- ram diameter [D; mm]: 6 mm, 8 mm, 16 mm,
- moisture content [u, %] 10-15 %, 15-20 %, 20-25 %,
- holding time on deformation [t; min]: 1 min. to 10 min., one mini reading intervals,
- pressure temperature [ϑ;°C]: 25°C; 80°C; 100°C; 150°C; 200°C.

CONCLUSIONS

The dissertation has reached the set objectives and presented the main results of research, that let we get clearer screen about high pressure compaction process of wood chips and dust sets. Main affecting factors have been identified, which greatly influence the density of pellet (wood species, pellet diameter, compression speed, compression pressure, particle size, moisture content, holding time on deformation, pressure temperature). Compression curves of the different particle size and hardness pointed out the role of external and internal voids during compression. That is the increasing of particle hardness firstly enable the reduction of external pores and only on specified pressure (~ 250 bars) enters the reduction of interiors pores. When the particle size decreased the pellet density also decreased and the relative residual deformation has increased. If the strength of particle size (pine) is getting smaller then the wood sets are more compressed on specified pressure. But end of the compressed process the wood sets were characterized lesser residual deformation; therefore the densities were also smaller compered to pellets of higher strength wood species (acacia). Have been observed that compared to the tendencies of higher pressure range the change in the mechanical behavior of wood chips and dust sets under low pressure load (bellow 500 bar) is contrary. That is, compaction mechanics of wood chips and dust sets anomalies are observed due to the decrease of the compaction pressure, which are explained in the ratio of particle hardness and external and internal pores. It has been specified with so-called pore theory.

The load (compression) speed also affected the density of pellets. If the speed is too fast (60 mm/min), then compared to the slower (2 mm/min) compression speed the density value of pellets were lower. The reason is that in case of very fast speed the deformation processes of wood chips and dust sets cannot able to execute sufficiently. That is, the deformation cannot follow the changes of speed due to the viscoelastic properties of wood. The wood chips and dust sets have more time for deformation and creep at lower speeds. It was established that in the tested fraction interval (0.063 to 1 mm) the changes of particle size does not affect significantly the density values of pellets. So that in all three wood species the differences was within ±5% around the most common fraction size (0.2-0.5mm). The harder and greater strength particle (acacia) was more resistant to the pressure, therefore end of compression the particle suffered less specific deformation (ε). Decreased the input deformation stress due to the lower specific deformation, resulting in become smaller the relative back suspension of pellets compered to pine. The back suspension rate is lower if the particle size of pellet is smaller, therefore have greater residual deformation. In practice, based on the research appropriate pellet density of the required performance requirements (~1100 kg/m^3) is achieve if the residual deformation min. $\varepsilon_m = 0.8$, about ε=0.8-0.85 specific deformation is needed under compression. Same density values in case of pine were achieved on higher pressure then acacia. This confirmed the legitimacy of different label widths in practice.

If increases the moisture content of raw materials the wood ability of plastic deformation also increases. That is a given pellet density can achieved with lower pressure until a certain limit moisture content of raw material. Under pressure the surface of the particles deforms (contact interface is changes) and the moisture leaves the wood portions, these are reducing the coefficient of frictions value. If the moisture content (between 12 %< u < 20%) of the pellet is increasing the mechanical durability is fading (with increasing moisture content also the heating value is fading), but the density is also increasing on average 7%. The examined fraction interval (0.2-1 mm) – over 20% moisture content of raw material – the pellet density values decreased and in many cases the pellets fell apart. The drying of raw material below 20 % of moisture content is anyway advisable in the practice. Influence of heat the wood as complex macromolecular systems is very complicated. This material under heat treatment goes through chemical and physico-chemical changes. The density of pellet increased when the temperature increases, because the wood sets have an affordable thermoplastic and deformation functions and the related mechanical changes in pore system of wood chips and dust stets. The density of pellet increased when the temperature increases but the relative back suspension decreased and the relative residual deformation increased. The pine's and acacia's pellet density increases in the temperature range of 80°C-200°C, these where in 15% in the examined particle size range (0.2-1 mm). The pelleting process is carried out on temperature 80-90°C. 900-1000 bar compression pressure is enough on this temperature for create the required pellet (1100 kg/m^3). 200 °C of compression pressure temperature for the same pellet density is enough about 700-800 bar pressure force; we can achieve approximately 20-30% compression power consumption reduction. Mechanically more durable and the density is bigger which pellet made in 200°C. That is, the energy density of pellet increased compared to traditional production process (partial torrification). The formed pellet which prepared on 200 °C have charred layer. This surface imparted the pellet hydrophobic property according to the literature. Heating the sticker to 200 °C has significant energy investment, therefor should take into account in economic decisions.

During relaxation and creep tests of wood chips and dust sets were determined the most important affecting factors, which had a significant effect to the process of relaxation and creep, exist: wood species, particle size, compression pressure, initial density of sets and temperature. The relaxation and creep is related to the solid density (compaction rate) of wood sets and stress magnitude of injected deformation at compression. Therefore, the higher compaction rate and deformation stress result less relaxation and creep of wood sets. The relative wall friction is significantly influence the pellet density. Increases of compression channel the density of pellet are increased. That is, increases the diameter proportionally reduced the effects of relative wall friction and thus also the pressure gradient along the length of pellet (seven times bigger wall effects has been established at 6 mm diameter compared to 16 mm diameter). Achieve a given pellet density (pine) needed ~30 percent greater pressure compered to acacia in case of identical ram diameter. 25-30 percent less pressure and rougher fraction is enough compared to the required pellet density (~1100 kg/m^3) if use 6 mm ram diameter then 16 mm. During the research of wall friction has been introduced a so-called relative area reduction factor (ψ), which allow as well as with measurements basis of some theoretical considerations has been approximate determined the changes of pushing force as function of pellet length. Using the approximate theoretical correlation of pushing force as well as the knowing of pushing force values has been determined the length of channel for the required holding compression, which is keeps the pressure at different pellet diameter. The obtained equation has been provided in non-dimensional form too.

The dissertation in addition to the rheology carried out research in side of energetic, on basis of these results to produce 1 m^3 pellet (density: 1000-1100 kg/m^3) the following parameter are required: 6 mm ram diameter and quasi 180-198 MJ (50-55 kWh) total work (compression and friction). According to additional research of energy consumption a dimensionless criteria equation has been developed to calculate the energy requirements that characterizes the pressure-density changes universally (independently from the wood species) as function of compaction work and press temperature at different pellet diameters. It was established that the most common fraction (0.2-1 mm) effect of 1400 bar compression the changes of specific work the characteristic curves are flat (exponent value is about -0.05), that does not change significantly the value of specific work as a function of particle size. The established criteria equation of (which based on the theoretical consideration) credibility and applicability has been verified by the results of measurements. The results obtained useful for theory and practice boundaries of engineer's accuracy.

THESES OF THE DISSERTATION

I did scientific conclusion in the following on the basis of detailed theoretical and experimental studies.

1. I have determined the differences in compression regularities various particle hardness of wood chips and dust sets including pellet density, back suspension, residual deformation, energy consumption and components of energy consumption as function of particle size, compression pressure, compression speed, moisture content and holding time on deformation. I also gave a theoretical explanation of the differences.

1. Taking account of the pellet stability (density requirements) I have given the minimum pressure value and energy requirements as a function of wood species, particle size, pellet diameter and temperature.

2. My research of wall friction, the growth of diameter after pellet pushing, as well as knowledge of the maximum pushing force values I have given the approximate mechanical calculating model of pushing force. Thus become possible to determine the component of the deformation modulus during compression, which is caused the wall friction at pushing. I generalized the data (dimensionless form), from which I can determine a critical channel length for a given pellet diameter. This provide the pre effect at arbitrary final pressure and pellet diameter

3. I used dimensional analysis to get similarity equation to calculate the energy consumption. This equation is applicable with any input parameters, regardless of the wood species.

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