IMPORTANCE OF TEMPERATURE, MOISTURE CONTENT, AND SPECIES FOR THE CONVERSION PROCESS OF WOOD RESIDUES INTO FUEL PELLETS

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Abstract. In wood pellet production, knowledge is needed about the raw material properties that affect the energy requirements for pelletizing and pellet quality. This study presents novel methods for this purpose, including analyses of influence of the raw material properties on the energy requirements in the sequence of subprocesses (compression, flow, and friction components) that constitute the pelletizing process, and the strength of the pellets. The methods were used to analyze the importance of pelletizing temperature and MC and the differences between sawdust of European beech (*Fagus sylvática* L) and Scots pine (*Pinus sylvestris* L). Results showed that increasing temperature and MC decreased the energy requirements for all components of the pelletizing process and that beech required more energy than pine in all components. Beech produced the stronger pellets; increasing temperature resulted in stronger pellets, whereas increasing MC caused weaker pellets. Also, a method to quantify the energy requirements for the combined pelletizing process is presented. The methods can be used to analyze the allocation of the energy requirements of pelletizing in the die and can be useful tools for analyzing the pelletizing properties of wood and other biomass residues.

Keywords: Wood pellets, pelletizing, biofuel, compression, friction, viscosity, adhesion, extractives, densification, sawdust.

INTRODUCTION

The raw materials for wood pellet production include wood residues (primarily sawdust) from primary and secondary wood processing industries.

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Cylindrical wood pellets have a 6 – 8 mm dia and are 5 – 40 mm in length and are used as fuel in residential heating and centralized heating and power production. In 2007, the worldwide market was approximately 8 million tonnes, which is expected to increase to 15 million tonnes by 2010 (Ljungblom 2007; Vinterbäck 2008). The raw materials can be characterized by the anatomical and chemical properties of the wood species, temperature, MC, preparation method, storage, and particle size distribution. These parameters illustrate the heterogeneous character of the raw materials coming from different suppliers and types of wood industries. These variations cause significant differences in the costs of pelletizing when different types of raw materials are used. The different costs are related to variations in the energy requirements to pelletize the raw materials because the pellet mill's capacity (t/h) is limited by the specific maximum power consumption of the pelletizing equipment. Therefore, raw materials that require more energy to pelletize lead to a lower production capacity along with higher maintenance costs per tonne of pellets. To minimize the cost of production and to optimize the use of new raw materials for the growing wood pellet market, better knowledge is needed on how the raw material's individual physical and chemical properties affect the energy requirement of the pelletizing process. The strength that the pellets obtain is an important quality parameter, and this also varies among raw materials. However, rapid and consistent methods are needed to analyze the raw material's effect on the energy requirements for pelletizing and pellet strength to increase the understanding of the connection between the wood properties and these factors in the process.

Figure 1 illustrates the pelletizing process, which essentially works by extruding (e.g., sawdust) through cylindrical press channels, which

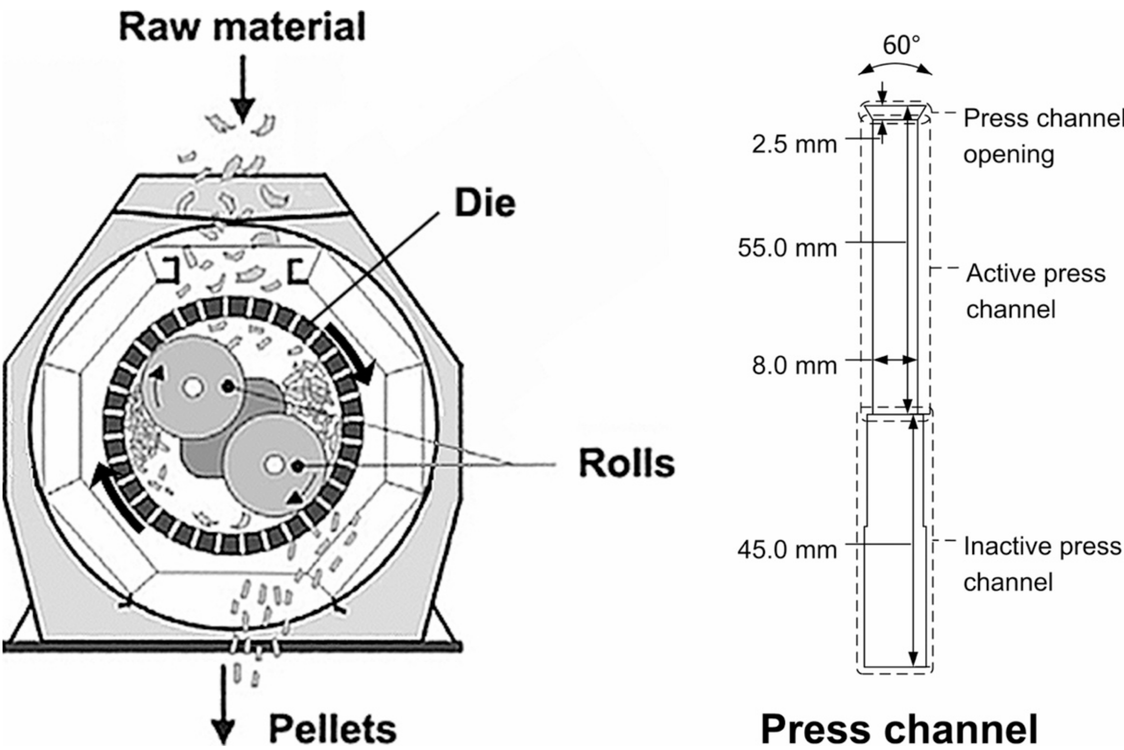

Figure 1. Illustration of the pellet mill and a press channel.

are 6- to 8-mm-dia holes drilled through a ring-shaped steel die. The figure (right) illustrates a press-channel design, in which the first part of the channel has a cone-shaped opening that can be 2.5 mm deep and with 60° angles and the total length of the active part of the channel can be 30 – 70 mm. The die (left) is typically a 150 – 250-mm-long steel cylinder with an inner diameter of 800 mm and outer diameter of 1 m. The press channels are arranged radially in close proximity in the die (see Fig 2). The press channel openings are on the die's inner surface and the channel exits on the outer surface. The number of channels in one die can be several thousands. Some thickness of the die cylinder is required for strength; therefore, the press channel also contains an inactive (downstream) part that does not contribute to pelletizing. Because of the distance between the channel openings on the die's inner surface, an area is present between the openings that may take up more than one-half of the die area depending on the press channel design.

Two to three bearing-mounted stationary rolls are located on the die's inner surface, and by rotation of the die, the rolls thus run on the press channel band. Sawdust is continuously added in front of the rolls, and the rotation of the die forces the sawdust into and through the channels. Because of the force required to press the sawdust into the channels and the friction, high pressure is built up under the rolls, which compresses and bonds the sawdust. Each time a channel opening is passed by a roll, a new layer is pressed into the channel and the downward movement in the channels therefore occurs in discrete steps. The process causes high-density (1200 – 1300 kg/m^3) pellets to be pressed out and break off from the press channel exits. The pelletizing process generates heat that maintains the temperature of the operating die at 110 – 130°C (unpublished data). The rotation of the die is the energy-requiring part of the process, whereas the rolls run passively on the press channel band. In the present work, the specific energy required to rotate the die for a given raw material is termed the specific work of pelletizing, W_{spec}.

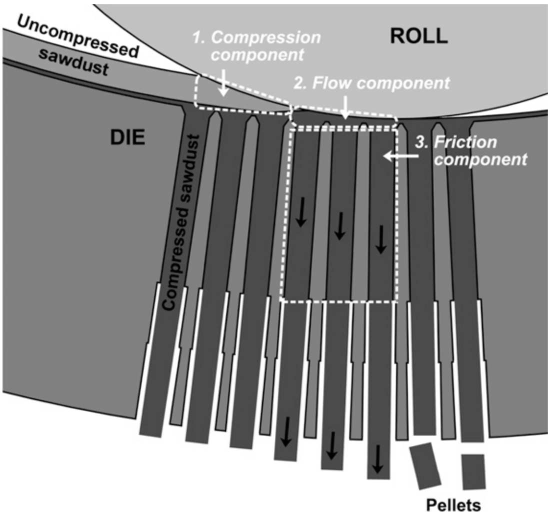

Figure 2. Illustration of the pelletizing process. A section of a press channel row is used to illustrate the die/roll/sawdust system. The components (see text) of the pelletizing process are allocated to the positions marked by the white dashed lines. The lower part of the press channels with larger diameter is not part of the pelletizing.

Figure 2 schematically illustrates the pelletizing process with a section of a channel row and shows that the process can be separated into component sequences of compression, flow, and friction of e.g., sawdust. Therefore, W_{spec} can be seen as the sum of the individual energy requirements for these components and therefore does not quantify or apportion the energy required for each component. The components may be differently affected by sawdust properties and therefore, to characterize where and how much the raw material properties cause variations in W_{spec}, the properties must be analyzed for each component.

The pelletizing process can further be described as the ratio between the force applied by the roll (F_{roll}) and the force required for downward movement of the compressed sawdust in the channels (F_{die}). When the roll approaches the die surface and F_{die} is highest, the sawdust temporarily forms a compressed layer on the die surface. When F_{roll} exceeds F_{die}, the material in the press channel is forced to move downward, and the sawdust in the compressed layer is distributed into the press channel openings. This process occurs under pressures ranging 210 – 450 MPa (Leaver 2000), which was confirmed in the present study, and some of the material in the compressed layer is located over the horizontal area in between the press-channel openings. This part of the layer must therefore be moved horizontally to enter a channel opening. Thus, F_{die} at this point is dependent on the strength and viscosity of the highly compressed layer because it must be separated to flow horizontally and to flow into the channel openings, and F_{die} is also dependent on the friction between the compressed sawdust and the press channel walls.

In the present work as illustrated in Fig 2, the compression component represents the energy to compress the sawdust (W_{comp}), the flow component represents the energy required to force the compressed layer into the press channels (W_{flow}), and the friction component represents the energy required to push the compressed sawdust in the channels (W_{fric}). These components are used to characterize pelletizing differences between samples. The pressure and temperature in the die cause the raw material particles to bond together probably by autoadhesion processes (Back 1987) as no adhesives are used in conventional pelletizing. The surface-to-surface bonding of the particles may contribute significantly to the strength of the pellets, and the extent of the bonding may be affected by extractives (Nielsen et al 2009a) and the MC.

This study presents laboratory procedures for measuring the raw material effects on the components combined with an analysis of the importance of die temperature and MC of the wood for pine and beech sawdust. Also, a method to measure W_{spec} is presented.

MATERIALS AND METHODS

Materials

Sawdust from European beech (*Fagus sylvatica* L) and Scots pine (*Pinus sylvestris* L) was prepared by chainsaw cutting across the grain producing sawdust with longitudinal fiber orientation (Nielsen et al 2009b) of dried boards bought at a local lumberyard. The chainsaw was operated without chain oil. The 1 – 4 mm particle size fraction was isolated using a Retsch sieve shaker to provide a homogenous sample. The samples were moisture-conditioned in desiccators with different saturated salt solutions for 14 da at 23°C. The MCs were measured with a Sartorius MA 30 moisture analyzer (see Table 1). The samples were kept at –18°C before further analyses to minimize the storage effect (Hse and Kuo 1988; Back 1991; Nielsen et al 2009c).

Methods

The pelletizing components were measured with dies and pistons produced for the purpose (Fig 3) in an Instron 4485 testing machine with a 200-kN load cell and a data logging system. The Instron system was used to push the press pistons and simultaneously measure the required position and force. Electrical heating (HSS braid coil, HT 30 regulator, Horst GmbH) was used to adjust the temperature of the dies.

Data for W_{comp} and W_{fric} were measured as illustrated by Fig 3a – b. The press channel diameter was 8 mm, and a pellet was made by compression of 0.750 g sawdust to 15-kN maximum force (≈300 MPa). Compression speed was 127 mm/min and the maximum force held for 10 s (Fig 3a). After the pressure was released and the stop piston removed, the pellet was pushed

Table 1. *Moisture content (oven-dry basis) after conditioning in desiccators.*

Salt solution	Pine	Beech
$MgCl_2$	6.0	5.8
CH_3COOK	8.1	7.9
BrNa (dried)	9.7	10.7
BrNa	11.3	12.1
NaCl	12.1	12.9
NaCl (moistened)	12.6	13.6
NaCl (moistened)	15.9	NA

"Dried" and "moistened" refer to drying (50°C) and water addition (aerosol) after conditioning, respectively.
NA, Not available.

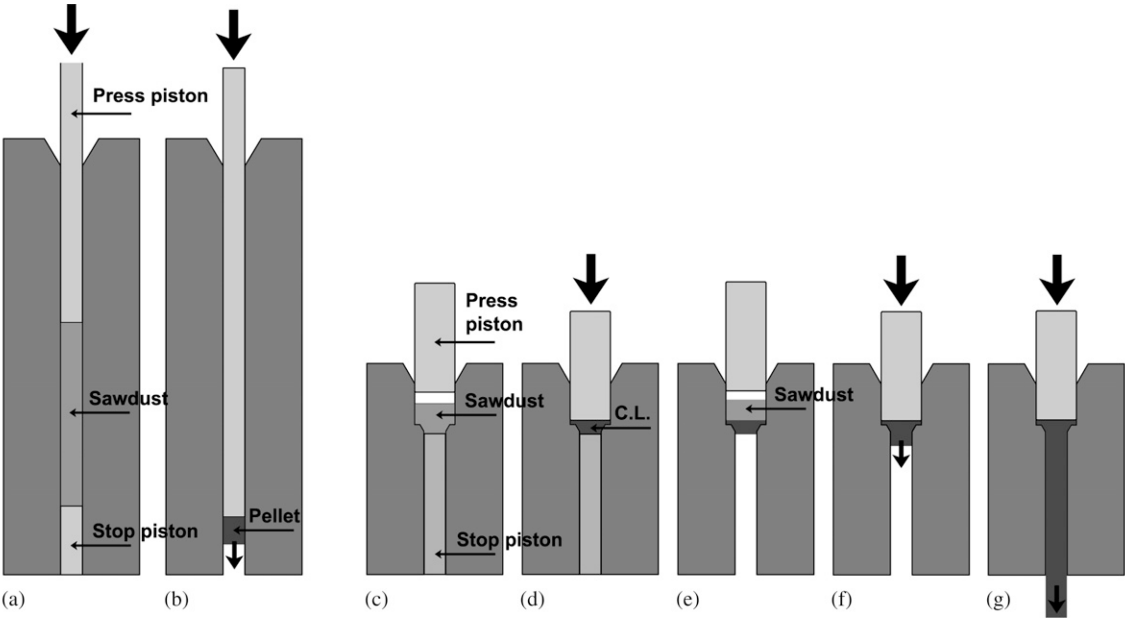

Figure 3. Illustrations of the two dies and test procedures. (a – b) The procedure for compression and friction analysis; (c – f) the flow analysis; (g) the continuous pelletizing.

3.5 mm in the press channel (Fig 3b). Pellet speed was 127 mm/min, and the pellet was subsequently pushed out of the channel. After 24-h cooling at 20 – 25°C and ambient RH, the pellet strength was measured by placing the pellet on the side and measuring the maximum force required to fracture it (Nielsen et al 2009b).

The W_{flow} measurement is illustrated in Fig 3c – f. The flow die was made to imitate the press channel of a commercially available press-channel design with a channel diameter of 8.0 mm and a 2.5-mm deep cone-shaped press channel opening with 60° angles. The cross-sectional area of the press piston chamber equaled the sum of the area of a press-channel opening and the associated horizontal surface area based on a commercial design. This resulted in a rim of horizontal area surrounding the Press channel opening (see Fig 2). The diameters were 10.89 mm (press channel opening) and 14.76 mm (press piston chamber). Press channel length was 40.00 mm, including the 2.5-mm channel opening. In the first step (Fig 3c – d), a compressed layer (CL) was formed in the press channel opening by compressing 0.75 g of sawdust. The press piston was stopped 1.00 mm above the press channel opening giving a compressed layer density of 1500 kg/m^3. In the second step (Fig 2e – f), the stop piston was removed and an additional 0.25 g (second layer) was similarly compressed causing the compressed layer to flow into the press channel. The press piston was stopped 1.00 mm above the press channel opening. Compression speed for both steps was 25.4 mm/min.

Continuous pelletizing (Fig 3g) was dome by successively pressing new layers (0.25 g) into the press channel, which eventually filled the channel, thus producing pellets and simulating the continuous pelletizing process.

The influence of temperature was measured with die temperatures of 60, 75, 85, 95, 105, 115, 125, 135, 145, and 160°C with pine and beech at 11.3 and 12.1% MC, respectively. Likewise, the influence of MC was measured in the range of 6 – 16% (Table 1) at a die temperature of 125°C. Continuous pelletizing was made with pine and beech at 11.3 and 12.1% MC, respectively, and with a 70/30 pine/beech mix, all at 125°C die temperature.

Data Analysis

The areas under the plots of the force vs press piston position data were used to calculate the energy required in the W_{comp}, W_{fric}, and W_{flow} measurements. Figure 4 illustrates the data (lines) and areas (gray) used for W_{comp} and W_{fric}, which is the energy used in each procedure. The larger the area, the more energy was required to compress the pellet and to push it in the channel. Figure 5 illustrates the pressing of the second layer in the flow procedure. W_{flow} was calculated as the area under the plot in Fig 5a. The point where compression of the second layer shifted into flow of the compressed layer was located from the slope inflection calculated from the W_{flow} plot in Fig 5a. Figure 5a shows a plot of the slopes in Fig 5a. The force at this point was used to calculate the corresponding pressure [force/(press piston area)] giving the flow initiation pressure (P_{flow}). Each layer in the continuous pelletizing process was analyzed in the flow measurements. A plot was made to illustrate the effect on W_{flow} from adding more layers to the press channel and the increase in friction from a longer pellet in the channel. The error bars in the figures illustrate standard error of the means.

RESULTS AND DISCUSSION

Compression Component

The effect of temperature (T) and MC on compression is illustrated in Fig 6a – b and it is seen that both factors had a significant effect on W_{comp}. In the temperature plot, a minimum was reached at approximately 105°C for both species. Pellet mass measurements (not presented) showed that T greater than 105°C caused significant sample drying during the procedure, which may explain this minimum. Increased moisture decreases the stiffness of the wood (Hillis and Rozsa 1978; Gerhards 1982), and therefore, the increase in W_{comp} at T less than 105°C most likely related to sample drying, which seems reasonable because the system was not sealed. This is supported by the importance of MC shown in Fig 7b, in which increasing MC caused a decrease in W_{comp} probably also related to the softening of lignin under these conditions (Goring 1963; Irvine 1984; Kelley et al 1987).

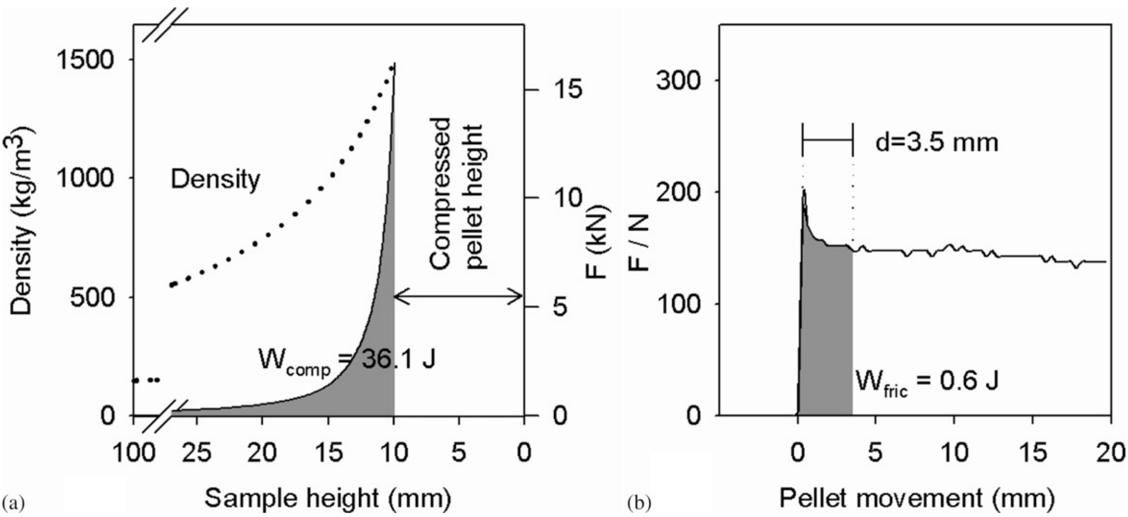

Figure 4. The data and areas used for W_{comp} and W_{fric}. (a) The pellet density is plotted to illustrate the compression. The area under the force vs position (mm) plot is used for W_{comp}. (b) Approximately 200 N was required to start the pellet movement, and the force vs position (mm) plot area used for (W_{fric}) is shown.

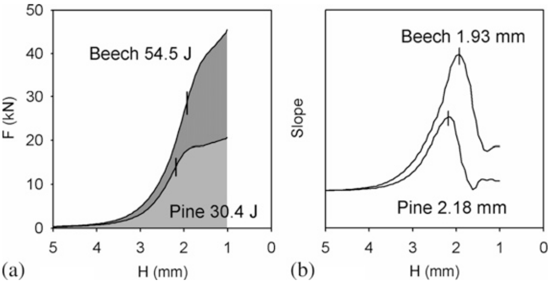

Figure 5. Illustration of the flow component data analysis. H is the height of the sawdust layer above the press channel opening. (b) The slopes of the plots in (a) and the positions of the slope optima, which are also marked in (a).

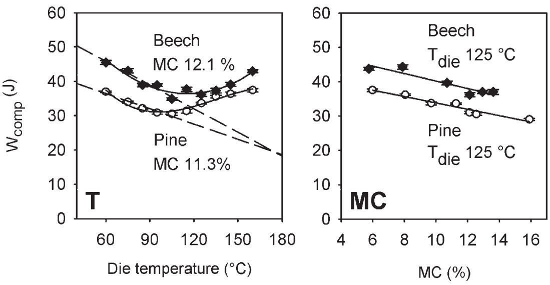

Figure 6. Importance of temperature (T) and MC for the energy required for compression. The dashed regressions in T are based on 60 – 105°C, $r^2_{pine} = 0.95$, $r^2_{beech} = 0.95$. In the MC plot, $r^2_{pine} = 0.94$, $r^2_{beech} = 0.88$.

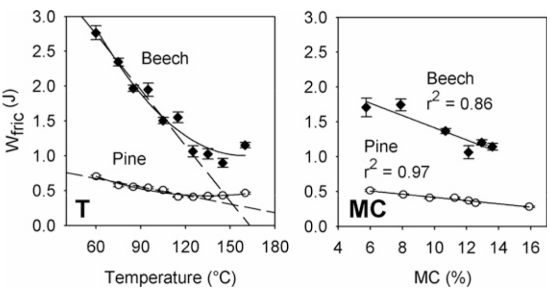

Figure 7. Importance of temperature (T) and MC for W_{fric}. The dashed regressions in the T plot are based on 60 – 105°C, $r^2_{pine} = 0.88$, $r^2_{beech} = 0.96$.

Also, it can be seen that the decrease in W_{comp} is not caused by simple replacement of wood with water because the increase in MC of 6 – 16% for pine caused a decrease in W_{comp} of 38 – 28 J (26% decrease) and likewise 6 – 14% MC and 45 – 37 J (18% decrease) for beech. A linear regression of W_{comp} (60 – 105°C) in Fig 6a illustrates a possible outcome in a sealed system with constant MC.

A stress vs density analysis (not shown) showed further differences in compressive properties between the species. Beech required a higher stress for compression than pine for all densities in the range of 200 – 1550 kg/m^3. Compression of sawdust compared with solid wood eliminates the difference in initial density between the samples, and therefore the analog of compression of pine and beech sawdust can be seen as the compression of solid pine and beech with the same density. Therefore, the difference between the two species cannot be explained by the conventional relation between density and hardness (Kollmann 1968). The effect could be related to the higher content of extractives in pine than beech (Fengel and Wegener 1989; Zule and Moze 2003; Josefsson et al 2006; Nielsen et al 2009b), which are reported to act as plasticizers (Matsunaga et al 2000) and probably lubricants in compression (Nielsen et al 2009a).

Friction Component

Figure 7 shows that friction (W_{fric}) was also minimized by increasing T and MC. The correlation between T and friction is supported by findings with pine on steel (McMillin et al 1970), but the correlation to MC contradicts other literature (Atack and Tabor 1958; Lemoine et al 1970; Guan et al 1983). These reports state that increasing MC increases the contact area and thereby the friction of solid wood on a platen because of softening of the wood. However, the softening effect on a compressed pellet could be insignificant for the contact area compared with uncompressed wood. The pellet surface is smooth, similar to the press channel wall in contrast to the rough and open character of the cell structure that characterizes the surface of uncompressed wood (Nielsen 2009). The contact area between the pellet and the press channel wall is therefore already substantial from compression, which could minimize the effect of softening. More importantly for the friction is that it may be related to bonding or interaction mechanisms between the wood and the surface of the steel (Atack and Tabor 1958). Therefore, the effect of increasing MC as seen in Fig 7 could be related to water acting as a mobile layer or lubricating agent (Bowden and Tabor 1966) between the pellet and the press channel wall.

The lower friction of the pine pellets may be caused by a higher extractives content leading to different friction properties and bonding strength between the sawdust particles compared with beech (Nielsen et al 2009a). The role of extractives on frictional properties has been previously described (McKenzie and Karpovich 1968; Lemoine et al 1970; McMillin et al 1970; Nielsen et al 2009b) in which extraction with various solvents increased the friction and that high extractives content involved low frictional properties. Scots pine contains more lipophilic extractives than European beech, 5 vs less than 1%, respectively (Fengel and Wegener 1989; Zule and Moze 2003; Josefsson et al 2006; Nielsen et al 2009b), which supports the findings in Fig 7. The strength of the beech pellets was significantly higher than the pine pellets (see below and Fig 10), which may affect the stress applied by the pellet to the press channel wall ($stress_{wall}$). As stress was applied in the compression component, $stress_{wall}$ also arose in the pellet because of strain in the wood perpendicular to the direction of the stress. It is assumed that the two sawdust types had the same fiber orientations because of the same cutting procedure and that the Poisson ratios (Bodig and Goodman 1973) were in the same range. However, as a result of the higher strength of the beech pellets, they maintained more $stress_{wall}$ compared with the pine pellets after compression, which increased the friction of beech. The assumption is supported by Nielsen et al (2009b) showing that pellet strength may affect $stress_{wall}$. However, the two explanations may be problematic to estimate because extractives affect both pellet strength and the frictional properties (Nielsen et al 2009a).

Pellet Strength

The effect of temperature and MC for pellet strength is presented in Fig 8. The bonding processes are most likely a combination of sawdust particle entanglement and autoadhesive surface bonding processes (Back 1987, 1991; Gardner 2006). Contact between the available sites for hydrogen bonding may therefore be crucial for the pellet strength. Water sorbs at hydrogen-bonding sites (Schneider 1980; Hartley et al 1992; Berthold et al 1996; Haygreen and Bowyer 1996) thus occupying sites for particle-to-particle bonding and may therefore decrease the pellet strength as seen in Fig 8 MC. This could also cause the increase in strength in Fig 8 T that may be related to drying as previously discussed. The difference between the species is assumed to be caused by differences in the extent of additional blocking of hydrogen-bonding sites by extractives forming a weak boundary layer (Stehr and Johansson 2000; Nussbaum and Sterley 2002). This phenomenon is also known as "surface inactivation," which refers to a time-dependent surface deposition of extractives, preventing access to the high-energy bonding sites on the structural wood surface (Back et al 2000; Gindl et al 2004). Surface deposition of extractives on sawdust has previously been shown (Nielsen et al 2009c), and in the present work, the deposition may have occurred during the moisture conditioning procedure. This effect of extractives can be higher for Scots pine because of the higher extractives content, which can explain the lower pellet

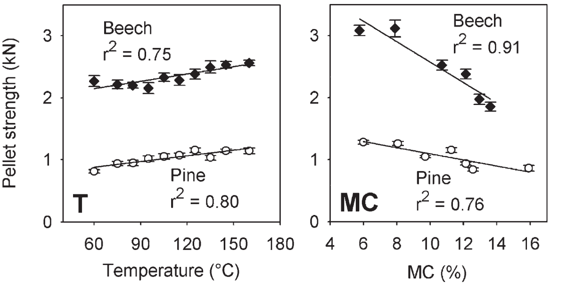

Figure 8. The effect of temperature and MC on the pellet strength.

strength compared with beech. It is also seen in Fig 8 MC that the effect of increasing MC is higher for beech (steeper slope) than for pine because water adsorption on a less contaminated surface (beech) may affect the strength more than on a more contaminated surface (pine) where a greater number of high-energy bonding sites are covered by extractives.

Flow Component

Figure 9 illustrates the second part of the flow procedure, which is used for W_{flow}, which is a combination of compression of the second layer and flow and friction of the compressed layer in the press channel opening. Therefore W_{flow} as illustrated in Fig 10 is the sum of the energy required for these processes. The shift between compression and flow occurs when the pressure reaches P_{flow} (see Fig 5), and Fig 11 shows that a negative correlation was found between P_{flow} and T and MC. A significant effect of drying is also seen in the T plot. P_{flow} may be closely related to the pellet strength, because the shift from compression to flow requires breaking of bonding between the particles in the compressed layer. This is supported by the increase in P_{flow} caused by drying in Fig 11, T, which correlates to the importance of MC on pellet strength (Fig 8, MC).

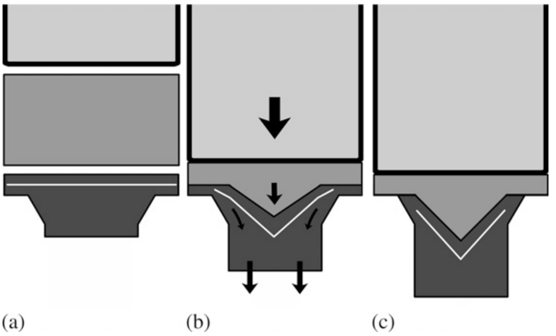

Figure 9. Illustration of the process in Fig 3e – f. (a) The second layer and the shape of the compressed layer. (b) Force is applied and the second layer is compressed and starts to force the compressed layer into the press channel opening and the press channel. (c) The press piston has been stopped 1 mm above the press channel opening. The white line refers to the initial position of the sawdust in the compressed layer.

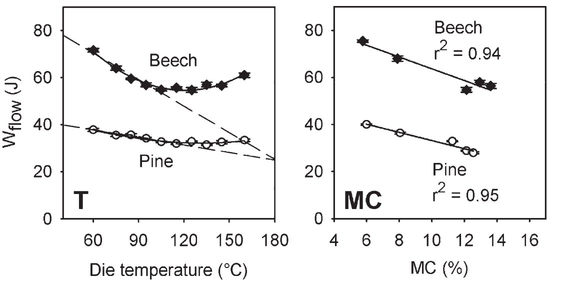

Figure 10. Importance of temperature (T) and MC for the W_{flow}. The dashed regressions in T are based on 60 – 105°C, r^2_{pine} = 0.95, r^2_{beech} = 0.96. The plots illustrate the energy required to compress and press 0.25 g of sawdust into the press channel.

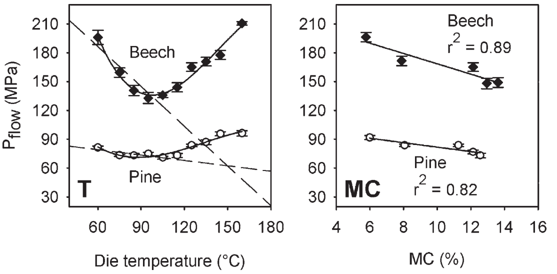

Figure 11. Correlation between P_{flow} and temperature (T)/MC. The dashed regressions in T are based on 60 – 105°C, r^2_{pine} = 0.69, r^2_{beech} = 0.85.

Following the shift from compression to flow, the compressed layer must be forced through the cone-shaped press-channel opening, and therefore its viscosity and friction affect the energy requirement for the flow. Figure 10 shows that W_{flow} was negatively correlated with T and MC and that drying also increased W_{flow} at T greater than 105°C. The viscosity and pellet strength may also be closely related because the bonding between the particles must be continuously broken as the layer of compressed sawdust is forced to change its shape, when it is pressed into the channel. However, in addition to the particle bonding, the viscous properties of the lignocellulose may also contribute to the W_{flow} because significant cell wall bending and deformation will be part of the process.

If the values for W_{comp}, and W_{fric} are subtracted from W_{flow}, the energy requirement for the viscous change in shape of the compressed layer can be estimated (W_{visc}). For beech at T = 60°C, W_{comp} = 46 J, W_{fric} = 2.8 J (both for 0.75 g), and W_{flow} = 72 J (for 0.25 g). W_{visc} can then be estimated by:

$$W_{visc} = 72J - \frac{46J \cdot 0.25}{0.75} - \frac{2.8J}{0.75} = 53J \quad (1)$$

Note that in the W_{flow} procedure, 0.25 g (second layer) is compressed and 1.0 g (compressed layer + second layer) is pushed 3.5 mm (not shown), which is also the distance for the W_{fric} measurement. For pine at T = 60°C, W_{flow} = 38 J vs W_{visc} = 25 J. This corresponds to 74 and 66% of W_{flow} for beech and pine, respectively, and shows that the majority of W_{flow} is allocated to the process of changing the shape of the compressed sawdust as it enters and passes the press channel opening. The difference between the species in W_{flow} (Fig 10) is therefore mainly caused by the difference in W_{visc}. This is supported by the species difference in P_{flow} (Fig 11) in which higher stress was required to initiate the flow of beech; hence, the physical strength of the pellet (bonding between the particles) was an important factor that may be closely related to the viscous properties of the compressed sawdust.

Continuous Pelletizing

In Fig 12, the continuous pelletizing process is illustrated as the increase in W_{flow} by successively pressing layers of sawdust into the channel. For pine, and the 70/30 pine/beech mix, a steady-state condition was reached after 15 – 17 layers, when the press channel was full and pellets were produced (Fig 3g). At steady state for pine, the pressure was 260 MPa when the press piston was 1 mm above the press channel opening and likewise 315 MPa for the 70/30 pine/beech mix. This is within the range of 210 – 450 MPa in a conventional pellet mill (Leaver 2000). The steady-state condition was not reached with beech because of mechanical limits of the test equipment when the force required on the press piston exceeded 120 kN (≈700 MPa).

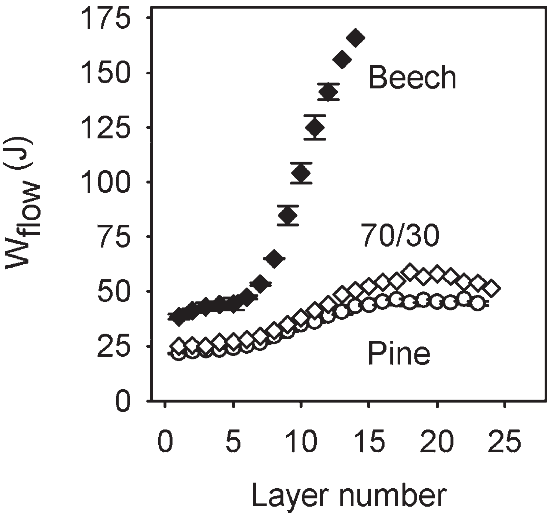

Figure 12. The increase in W_{flow} when pressing layers successively into the press channel.

Each layer in Fig 12 resulted in an increase in pellet length of approximately 3.5 mm; thus, based on the friction findings in Fig 7, it would be expected that W_{flow} would increase with 15 (layers) × 1.0 J (the energy required to push the compressed beech 3.5 mm) and correspondingly 15 × 0.4 J for pine, assuming that W_{fric} could be linearly extrapolated. However, Fig 12 shows that the increase in W_{flow} is not linearly correlated to the number of layers. The finding supports previous work (Holm et al 2006, 2007) in which data and models incorporating the Poisson ratios of wood show that the stress on the press channel increases exponentially with increasing pellet length in the channel, thereby increasing the friction exponentially as seen in Fig 12.

Figure 12 also shows that the difference between species can be separated between the differences in layer numbers 1 – 7 and after layer 7. This may indicate that the difference in layers 1 – 7 was dominated by the difference in W_{visc}, which was constant, and the small increase up to layer 7 was more or less linearly correlated with the W_{fric} data in Fig 7. After layer 7, however, the

W_{flow} of beech increased more than pine. The model in Holm et al (2006) explains this difference between species by their individual correlations between the stress to move the pellet (pressure) and the compression ratio (pellet length/diameter). The model predicts a smaller ratio (shorter pellet) of beech compared with pine before a steep increase occurs in the pressure for pellet movement, and layer 7 appears to initiate this for beech in the present study. Therefore, a press-channel length resulting in pellets after layers 7 – 9 for beech could result in a similar W_{spec} for pelletizing than for pine with the present press channel length.

The continuous pelletizing method enables a quantitative analysis to compare the specific energy requirements for pelletizing (W_{spec}). Figure 12 shows that at steady-state pelletizing of pine, W_{flow} of processing 0.25 g was approximately 45 J, and this corresponds to $\approx$180 MJ/t, which is agreement with conventional pellet mill energy measurements by the authors (not presented). Likewise, the 70/30 pine/beech mix would require approximately 22 MJ/t based on Fig 12, which is a 20% increase compared with pine. Also, it can be noted that for pine at 125°C, W_{visc} was 20 J (not shown), which corresponds to 44% of the W_{flow} (45 J) for the continuous pelletizing process at steady state. This shows that almost one-half of W_{spec} is used in the process allocated to the press channel opening where the compressed sawdust layer must flow into the channels.

CONCLUSIONS

This article has presented tools and methods that separate the pelletizing process into compression, flow, and friction components to measure the importance of raw materials properties for the energy requirements of pelletizing and pellet strength. The study showed that in all components, European beech sawdust required more energy to process than Scots pine and that increasing temperature and MC decreased the energy requirements for both species. It was shown that a significant part of the energy for the pelletizing process is allocated to the process of forcing the compressed sawdust from the surface of the die into the press channels. It was also shown that beech produced the strongest pellets, and it is suggested that the sawdust's bonding properties are an important factor for the energy required in the pelletizing process. The high bonding strength of beech was reflected in the energy required to force the compressed sawdust into the channels and to high friction in the press channels. The magnitude of these may be correlated with a greater number of high-energy bonding sites (e.g., hydroxyl groups) for bonding in beech than pine because of the lower extractives content in beech. Also, a method to measure the energy requirement in the continuous pelletizing process was shown to provide data comparable to an industrial pellet mill.

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