Research on Effect of Spruce Sawdust with Added Starch on Flowability and Pelletization of the Material

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Abstract

To verify the effect of added starch on flowability and pelletization of spruce sawdust, were prepared mixtures with addition of 0, 5, 10, 15 and 20 % (w/w) starch. The measured basic mechanical-physical properties of the individual mixtures have shown that starch improves flowability of the mixture (growing value of the ffc parameter), reduces impact of friction forces on the contact stainless material (reduced wall friction), thus reducing energy demands of the process as regards flow of the mixture through the hopper of a pellet press. High-speed camera simulations, which evaluate the immediate speed of particles during discharge of the hopper, have proved that addition of a material with different distribution of size and shape of the particles (starch) has a favourable effect on the overall flowability of the mixture. When pelletizing a mixture with starch, which has a lower angle of internal friction, the pelletizing pressure in the die is slightly lower and the resulting pellets have a slightly lower density. This feature is compensated by prevailing positive effects of the added starch on the pelletization, where the resulting pellets have higher durability, higher hardness and moisture resistance.

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1. Introduction

Pelletization is a process widely used in biomass processing. During pelletization, the pelletized material is transported. Flowability of these materials affect smoothness of the transport and verification of their properties can prevent development of arching or blockage of the transport routes [1], [2], [3], [4], [5] and the subsequent interruption of the pelleting process. Material properties such as the angle of internal friction and wall friction also affect construction of the silos [6]. The research is to evaluate flowability of artificially prepared mixtures in comparison with resulting properties of the pellets. We chose sawdust from common spruce (Picea abies) as a representative of one of the most widespread materials for pelleting in the world. To verify change of the properties, we used mixtures of pure spruce sawdust and spruce sawdust with added starch as a binding agent represented by 5, 10, 15 and 20 %. To evaluated impact of the added starch on transport and pelleting, we deliberately used mixtures with a content of starch higher than the standard amount (usually up to 2 %) [7]. The spruce sawdust can also be pelleted independently [7], [8]. In pelleting of pure spruce sawdust, the binding agent is lignin, which is present in the wood [9]. Additives used in pelleting include starch [7], [10], [11], molasses [12], [13], [14], [15], lignin from the wood processing industry [16], rapeseed flour, coffee meal, bark or pine cones [17]. A higher content of binding agents is used in pelleting and briquetting of charcoal or pyrolysis char [12], [13], [14], [18], [19].

Factors that affect transport of the material include granulometry of the material [5], [20], [21], [22], shape of the particles [5], [21], plasticity, deformability, solubility [23], hydrophobicity, wetting ability and cohesion between particles [24]. These properties also affect the pelleting. Regarding external factors, transport of the material is affected by moisture (formation of capillary forces) [24], temperature, pressure and vibrations [23].

The following parameters have been specified for description of the pelleting mixtures: granulometry, the angle of internal friction and wall friction, moisture, bulk density and the flowability. The following parameters have been specified for description of the pellets' mechanical properties: mechanical resistance, hardness, density and moisture resistance.

2. Materials and methods

The following instruments were used to determine properties of the input mixtures and the produced pellets.

2.1. Powders and their physical properties

Two basic ingredients were used in research on the effect of bonding agents on the flowability and the pelleting process - modified wheat starch and spruce sawdust. Moisture of these materials was measured by an instrument Excellence Plus HX 204 (Metler Toledo), the bulk density by a measuring cylinder and distribution of the particles' size by a laser analyser Cilas 1190.

2.2. Flowability, effective angle of internal friction and angle of wall friction

The angle of internal friction and wall friction was measured in the Laboratory of Bulk Materials at VSB-TU Ostrava with a ring shear tester Schulze R01. Flow profiles of artificially composed mixtures were recorded by a Lavision high-speed camera.

The automatic computer-controlled RST-01 (Ring Shear Tester) machine was designed by a German inventor Dr. Dietmar Schulz [25], [26] in agreement with established standards on shear testing of bulk
materials. Measurement with the RST machine starts with pouring the measured material in a shear cell. Then, the layer is levelled to the edge and the cell is weighed by analytic scales together with the material. After writing down the value, the measuring cell is placed on a spike, which passes through the centre of the table, and covered with a shear lid to which a rod producing the normal force is attached. Subsequently, counterweights are attached to the lid and two connecting rods, which link the lid to the tension force sensors, are inserted. The shear cell is rotated clockwise by means of the spike. The connecting rods prevent rotation of the shear lid through the bulk material by transferring the forces to the sensor. The shear stress, which is rising together with the rising normal load, is then measured. The outcome of the measurement is a line describing a linearized angle of internal friction, which specifies flow characteristics of the measured bulk material.

PIV (Particle Image Velocimetry) [27] is an optical method used in visualization of gas or fluid flows. In our case, however, it concerns sensing the particles' immediate speed in the bulk material. During the measurement, the recorded model should be correctly illuminated for the subsequent computer processing of the image. In this way, we can obtain a vector map of the flow field velocity. The principle is based on a light beam, which is modified into the shape of a light knife by a cylindrical lens, illuminating the measured surface. Data from several measurements on one level or data from several measurements on parallel levels can be further processed by a data processor, which will produce medium values of speeds on the researched level with higher accuracy.

The measurement is achieved by two or more brief successive pulses of known frequency, thus producing images in successive time intervals. The PIV processor determines positions of the particles in each image (one measurement) and evaluates shift of Δx and Δy particles in two mutually perpendicular directions. To evaluate shift of the Δx and Δy particles, it is necessary to know the scale of the image. The processor will determine components of the vx and vy speeds in the given spot from the known interval between images Δτ and from shift of Δx and Δy particles according relations 1 and 2.

\[
v_x = \frac{\Delta x}{\Delta \tau} \quad (1)\]
\[
v_y = \frac{\Delta y}{\Delta \tau} \quad (2)
\]

The whole process of measurement by the PIV processor lasts only several milliseconds. In this way, it is possible to visualize a vector map of the velocity field in the real time.

2.3. Pelletization

The spruce sawdust were crushed to the suitable grain size were by hammer crusher Green Energy 9FQ 50 to the suitable grain size. Hammer crusher has sieve with mesh size two millimeters. Airflow creating by hammers rotations has transporte crushed biomass to the bag.

A laboratory pellet press KAHL 14 – 175 was used for the pelletization. The pellet press has a flat die, the diameter of the produced pellets was 6 mm. A single die was used to keep identical pelletizing conditions.

2.4. Biomass pellet analysis

Durability of the pellets were determined by a Holmen NHP 100 tester. The machine is based on the Lingnotester principle. Pellet durability tester has been consist of feeding chamber, where are pneumatically circulated pellets sample. Chamber has inversed pyramid shape. The walls of chamber are performated.
Pellets are circulated at chamber. Production of fines particles or fragments is possible, when pellets strike to the wall surface or to themselves. Fines and fragments are sieved by perforated walls of testing chamber. Difference between pellet weight before and after the test expressed as a percentage is result of measurement, called Pellet Durability Index (PDI).

Hardness of the pellets was determined by a hardness tester KAHL ak14. KAHL hardness tester has works on function of gradually increasing press on pellet. Pressing is increasing until the pellet crash, strike or has been deformed. Press is simulated by the string principle. String has one end created by the tip, which are pressing on pellet. Resulting value is deducted (expressed in kilograms) when pellet has crashed, strike or has been deformed.

Density of the pellets was determined by a density tester Mettler Toledo JEW-DNY-43. The density is based on a difference of weights between a pellet sample in the air and a pellet sample in distilled water.

Moisture resistance is determined as a percentage expressed ratio between the weight of the pellet soaked in distilled water for 30 seconds and weight of the dry pellet compared with the weight before the testing [28], [29].

3. Results and discussion

3.1. Physical properties of the raw materials

Table 1 summarizes the measured basic physical properties of the sawdust and the starch. Particle size distribution of the sawdust is very wide. There are particles ranging from 5 μm up to 2 mm, but 50 % of the particles are up to 218 μm. The sawdust have needle-like shape, as illustrated in a microscopic photo (Fig. 1). Unlike the sawdust, particles of the starch are more ball-like and 50 % of them are up to 55 μm. The microscopic photo shows that the starch particles create clusters. This phenomenon can also be attributed to higher moisture (7, 8 %). The bulk density values support the notion that the sawdust will take more space in the hopper and additional starch content will increase the bulk density (Tab. 1), i.e. reduce space necessary for storage of the mixture or the actual process. If the maximum content of starch is 20 %, as in this case, this effect is not so apparent.

Table 1. Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>d10 (μm)</th>
<th>d50 (μm)</th>
<th>d90 (μm)</th>
<th>Moisture (%)</th>
<th>Bulk density (kg.m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>starch</td>
<td>80.80</td>
<td>217.88</td>
<td>339.10</td>
<td>7.76</td>
<td>464</td>
</tr>
<tr>
<td>sawdust</td>
<td>5.19</td>
<td>57.41</td>
<td>457.10</td>
<td>4.27</td>
<td>204</td>
</tr>
</tbody>
</table>

These measured basic characteristics suggest that sawdust, due to the particle shape, will show worse flow properties preventing trouble-free flow from the hopper, hampering the pelletizing process or further processing of this material (tableting, granulation etc.).
3.2. Flow properties

Table 2 shows the measured results of the effective angle of internal friction, the angle of wall friction, the bulk density and flowability of the individual mixtures.

For each sample, five yield loci were measurement by varying the consolidation stress $\sigma_1$ in the range between 1500 Pa and 15 000 Pa. After it, the values of the compression strength $\sigma_c$ were obtained from the yield loci. The flowability was then calculated for each yield locus as shown in equation 3.

$$ ff = \frac{\sigma_1}{\sigma_2} $$

The evaluation was based on classification of the flow indexes [30]. The results show that flowability of mixtures with starch was rising (Table 2). According to the flow characteristics, mixtures with ID 1 to 4 were included in the easy-flowing group of materials unlike the last mixture, which contained 20 % of starch and was classified as free-flowing with a double value of 14 as opposed to the pure sawdust mixture.

Table 2. Results of the measured values

<table>
<thead>
<tr>
<th>Mixture</th>
<th>ID</th>
<th>Angle of wall friction (°)</th>
<th>Effective angle of internal friction (°)</th>
<th>Flowability (°)</th>
<th>Bulk density (kg.m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% sawdust</td>
<td>1</td>
<td>13.3</td>
<td>43.3</td>
<td>6.6</td>
<td>204</td>
</tr>
<tr>
<td>95% sawdust + 5% starch</td>
<td>2</td>
<td>12.4</td>
<td>43.5</td>
<td>8.4</td>
<td>231</td>
</tr>
<tr>
<td>90% sawdust + 10% starch</td>
<td>3</td>
<td>11.6</td>
<td>43.8</td>
<td>9.2</td>
<td>221</td>
</tr>
<tr>
<td>85% sawdust + 15% starch</td>
<td>4</td>
<td>10.0</td>
<td>43.3</td>
<td>9.8</td>
<td>231</td>
</tr>
<tr>
<td>80% sawdust + 20% starch</td>
<td>5</td>
<td>9.5</td>
<td>43.1</td>
<td>14.0</td>
<td>253</td>
</tr>
</tbody>
</table>

The growing trend of bulk density in mixtures with starch can be explained by addition of ever rising amount of higher-density material than the actual sawdust. As it is evident from table 2, the angle of wall friction drops with the starch, which suggests reduction of friction forces between the sample and the tested stainless material with which the mixture is in contact inside the pellet machine. The starch reduces energy demands for flow of the mixture through the hopper. Addition of the binding agent affected the angle of wall friction more significantly than the angle of internal friction, which differed only slightly. This result suggests
that addition of starch does not have a great effect on the effective angle of internal friction.

We simulated flow from the hopper by limit mixtures, i.e. 100% of sawdust (ID 1) and 80% with 20% of starch (ID 5). For practical modelling, we used a glass model of a pellet machine hopper and a high-speed camera (chapter 2.2.). Simulation of discharge divided into 4 phases for mixtures 1 and 5 are illustrated in figures 2 to 9.

Fig 2. Mixture 1, Phase 1 – Opening of the output.
Fig 3. Mixture 1, Phase 2 – formation of an arch.
Fig 4. Mixture 1, Phase 3.
Fig 5. Mixture 1, Phase 4 – tear of the arch.
Fig 6. Mixture 5, Phase 1 – opening of the output.
Fig 7. Mixture 5, Phase 2 - free flow.
Fig 8. Mixture 5, Phase 3.
Fig 9. Mixture 5, Phase 4 – termination of discharge.

We can observe an area where the flow occurs and small bubbles are formed shortly after opening the hopper shutter filled with pure sawdust (Mixture 1, Phase 1). Illustration on the right shows a vector map of the material movement in the given area. These speeds are not high, about 0.50 m.s⁻¹, and the colour scale suggests that the material flows freely without significant loss of energy. Figure 3 (Mixture 1, Phase 2) shows
breach of the continuous flow. No other particles flow into the formed bubble from the adjoining area. An arch develops as a result of a large amount of contacts between individual particles, distributing the vertical stress onto the walls. The loose mixture under the developed arch is still freely flowing (Fig. 4). The arch illustrated in Fig. 5 (Mixture 1, phase 4) became released, thus allowing partial drain of material located over the discharge; however, even this chimney effect is undesirable during discharging of the hopper (a storage tank).

Simulation of a flow from hopper for the ID 5 mixture is illustrated in figures 6 to 9. The layer of material was released and smaller bubbles appeared after opening the output of hopper (Fig. 6 and 7). In this phase, the material freely flows above the discharge hole. We can also observe slightly yellow colouring in the area (ca 0.7 m.s⁻¹), which suggests lower losses of energy caused by internal friction (Fig. 8). This illustration also supports the theory that a mixture composed of sawdust and starch (ID 5) has better flow properties than pure sawdust (ID 1). Almost all of the material above the discharge hole is freely flowing. The arch does not develop and the colour separation of individual zones shows that particles rubbing against the developed wall of the chimney are slowed down by internal friction. Bonds that developed between particles of sawdust and particles of starch appear less cohesive in this illustration. This conclusion applies only for the researched dry mixture at normal temperature. If the starch particles are moistened and heated, they swell and the starch is thus acting as a suitable bonding agent in pellet production. This combined feature is welcome in the pelletization process - a freely flowing material in the hopper, which changes its flow property to compact material during the pelletization process by the effect of temperature (and moisture). It is possible to summarize the visual findings in the final phase of the ID 5 mixture discharge from the hopper. Unlike pure sawdust, the material was completely drained above the discharge hole without development of the arch. The cohesive stress of the researched material, however, is too high, thus preventing drainage of material in an area above the walls of the tank. The likely cause is a needle-like shape of the sawdust particles, which resemble "sharp-edged splinters". These particles tend to produce more solid bonds. The particles can touch each other not only in points, but also along their surface, which increases the inter-particle friction. By adding starch with ball-like particles, wedging of the needle-like sawdust particles is partially disturbed. Internal friction in a material containing 20 % of starch is slightly reduced, thus improving the flow properties (Tab. 2).

3.3. Pelletization process and pellets' properties

Moisture content of the pelletized material was 13 %. Duration of the material in the die remained identical. The die temperature was about 100°C. The results of durability confirmed increased durability with added starch as a binding agent, specified in reference [31]. A die with low compression ratio was deliberately used to suppress a high-pressure effect. If a die with a higher compression ratio were used, the pellets would have a higher quality, but the effect of the added starch on pelletization of spruce sawdust would not be so evident. The low pressure in pelletization of spruce sawdust produced fragments of pellets, which exceeded the length of 3.15 mm specified by the standard (EN 15210-1:2009), so they were included in a test of the pellets’ durability. These fragments reduced the resulting durability. Consequently, the durability dropped to 70.3 %. Without the fragments, the durability would be higher, around 98 %.

Hardness of pellets made from pure spruce wood, expressed as a load by weight, was 40 kg. Hardness of the pellets increased with added starch. Pellets made with a content of starch higher than 10 % reached hardness values exceeding the range of the tester, which has the maximum capacity of 50 kg. Moisture resistance increased with added starch. Pellets made from pure wood had the lowest moisture resistance. They absorbed 37.9 % of water during the test. The least absorbent pellets were pellets with 20 % additive; the value of absorbed water was 9.4 %.
The density of the pellets dropped with the added starch. The range of density moved between 1,230 – 1,290 kg.m\(^{-3}\). The average value was 1,570 kg.m\(^{-3}\).

**Table 3. Mechanical properties and density of the pellets**

<table>
<thead>
<tr>
<th>Sample of the pellets</th>
<th>PDI (%)</th>
<th>Hardness (kg)</th>
<th>WI (%)</th>
<th>Density (kg.m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% sawdust</td>
<td>70.3</td>
<td>40</td>
<td>37.9</td>
<td>1290</td>
</tr>
<tr>
<td>95 % spruce sawdust + 5 % starch</td>
<td>80.9</td>
<td>50</td>
<td>20.3</td>
<td>1260</td>
</tr>
<tr>
<td>90 % spruce sawdust + 10 % starch</td>
<td>84.4</td>
<td>&gt; 50</td>
<td>14.7</td>
<td>1250</td>
</tr>
<tr>
<td>85 % spruce sawdust + 15 % starch</td>
<td>94.0</td>
<td>&gt; 50</td>
<td>14.7</td>
<td>1250</td>
</tr>
<tr>
<td>80 % spruce sawdust + 20 % starch</td>
<td>99.2</td>
<td>&gt; 50</td>
<td>9.4</td>
<td>1230</td>
</tr>
</tbody>
</table>

![Fig 10. Effect of added starch on the mixture properties](image1)

![Fig 11. Effect of added starch on the pellet properties](image2)

**4. Conclusion**

It has been detected that behaviour of mixtures with various representations of starch can be predicted by their basic characteristics and simulation of the flow. It is evident that starch is a binding agent, which reduces the angle of wall friction, i.e. reduces energy demands during discharge of the pellet press hopper. The flowability of the material is also better. Comparison of flow simulations without starch and with 20 % added starch shows that in the latter condition, the material is completely drained above the discharge output without formation of an arch during the process. The needle-like shape of the prevailing quantity of sawdust, however, causes greater cohesion of the mixture on the hopper wall, thus slightly slowing down the flowing particles due to internal friction in this wall layer. In case of pure sawdust (ID 1), development of the arch would already be observed in phase 2.

In pelletization of ID 5 mixture, a lower pressure was applied on the material in the die due to a lower angle of wall friction; consequently, pellets with a lower density were produced. Addition of starch allowed production of pellets with higher durability, hardness and moisture resistance.
Starch is a suitable binding agent for processing of the given type of biomass. It improves flow properties of spruce sawdust, but most importantly, improves quality of the produced pellets.

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