LogistEC

Logistics for Energy Crops' Biomass

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Assessment of improved densification technologies

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Glossary and Definitions

ExCom	Executive Committee
w.b.	Wet based
d.b.	Dry based
Durability	Durability is a measure of the pellets/briquettes ability to withstand destructive forces such as compression, impact, and shear during handling and transportation [1].
Additive	An additive is a material, which is intentionally introduced into the pellet production, or is added after production, to improve the quality of fuel, reduce emissions or make production more efficient.
Compression ratio	Also known as 'aspect ratio' or 'l/D'. It is the ratio between length and diameter of press channel in the pellet mill.
Pelletizing pressure	It is the pressure necessary to overcome the back pressure built up in the press channel.
Relaxation	When the briquette is removed from the die there is an immediate elastic recovery which is principally evident in an increase in axial length but there is also a small expansion along orthogonal axes. There is then a period of delayed or retarded elastic recovery, which is complete after a particular time, when the briquette attains its final and stable dimensions.
wt%	Weight of a fraction in a sample divided by the total weight of a sample, expressed as a percentage.

Summary

Objectives set up the experimental plan for the nine biomass species

Rationale: There is currently no literature review on the densification of all nine biomass species investigated in LogistEC, and there is lack of comparison of pelletizing and briquetting.

Teams involved: Risø DTU, CFN, ECN

Geographical areas covered: Not applicable

The aim of this deliverable is to assess the densification technologies based on the existing literature and previous in-house experience with same or similar biomass species, e.g. miscanthus and triticale. A literature survey has been done regarding densification (pelletizing and briquetting) of nine biomass species (triticale, miscanthus, willow, eucalyptus, poplar, giant reed, tall fescue, alfalfa, sorghum) according to the DoW. A brief introduction of these two technologies regarding the process and different types of machine is given. Some key process parameters are introduced for both densification methods and the influence of these parameters to the product quality is explained. The optimal process conditions found for the target biomass species are listed as a reference for choosing the test conditions in our experiment. However, the information is only available for some species. In the end, the experimental plans and machines used for pelletizing and briquetting are described.

The experimental results will be included in D3.2 (Preliminary quality characteristics of commoditized energy crops) and D3.3 (Improved densification recipes for raw energy crops). The work on pelletizing torrefied and torwashed biomass will be described and carried out in D3.5 (Improved densification recipes for thermally pre-treated energy crops). Teams involved in D3.1 are Risø DTU and CFN. The WP leader from ECN validates the table of contents before drafting the deliverable, and approves the final version.

1. Densification technologies

The standard shape of a fuel pellet is cylindrical, with a diameter of 6 to 8 mm and a length of no more than 38 mm. If the pellets are with more than 25 mm in diameter, they are usually referred to as 'briquettes' [1].

1.1. Pelletizing

1.1.1. Introduction

The pelletization process takes place in the press channel of a pellet mill. A typical ring die pellet mill consists of a die with press channels and eccentrically installed rollers. During pelletization, biomass particles are fed into the mill and squeezed between roller and die, forced to flow into and through the press channels. Every time the roller passes the channel, the raw biomass is pressed into the channel, and a layered structure of the pellet is produced [2]. However, using pilot scale pelletizers to study the effects of different parameters is time and material consuming, and some process parameters cannot be easily controlled since they are connected but dependent on each other. For example, die temperature is influenced by the friction and the friction depends on the press channel length [3].

Single pellet press testing is a widely used method for testing the pelletizing properties of new types of biomass. The effects of die temperature, pressure, moisture content, biomass species and additives can be quickly screened in the single pellet press before scaling up the trials [4]. The press consists of a cylindrical die and a metal piston. The end of the die is closed using a removable backstop. The die temperature can be controlled by heating elements, the piston movement and force applied to make a pellet can be monitored continuously. To simulate the pelletizing process within a commercial pellet mill, the pellet had to be built up in sequential layers.

1.1.2. Key process parameters

1.1.1.1. Particle size

The optimal particle size depends on the densification process. For instance briquetting processes can in general tolerate larger particles than pelletizing process. For pellet production, particles are usually below 5 mm in diameter. In general, a broad variation of particle size is best with respect to pellet quality. However, too high amount of fines (particles < Ø 0.5 mm) in the raw material has a negative impact both on friction and pellet quality. As a rule of thumb, the amount of fines should not exceed 10 -20% unless a binding agent is added [2].

In a study of alfalfa pellet durability, Hill and Pulkinen [5] noted an increase in hammer mill screen size from 2.8 to 6.4 mm reduced the durability by more than 15%.

1.1.1.2. Moisture content

The effect of raw material moisture content on the pelletizing properties and product quality has been the subject of several studies [2]. In general, the optimum moisture content for wood species was found to be between 5 -10 wt%, while it was significantly higher for grasses as between 10 -20 wt%. Increasing moisture contents above the optimum have been shown to have a negative influence on the pellets' mechanical properties. Therefore, determination of optimal moisture content of the pellets, which varies by biomass type, is required for production of stable and durable pellets.

From Risø DTU's experience, this issue is especially pronounced for torrefied biomass. The ability of biomass to absorb water decreases with the increase of torrefaction temperature since the number of hydrogen bonding sites decrease with thermal degradation of hemicellulose, cellulose and lignin. For biomass torrefied at high temperatures, most of the added water is adsorbed at the surface and in the pores of the material rather than being bound to the polymers by hydrogen bonding. This will likely reduce the ability of water to act as a plasticizer and its ability to lower the softening temperature of the biomass polymers. Instead of having a positive effect, an excess of water might actually have a negative effect on the pelletizing properties. This has already been observed in our earlier work [4]. Therefore, the optimal amount of water to be added to improve the pelletization of torrefied biomass is depending on the torrefaction condition and need to be determined by testing.

1.1.1.3. Die temperature

The increase in mechanical properties of the pellets with an increase in die temperature was reported for spruce, corn stover, switchgrass, pine, olive residue, beech, and wheat straw [2]. It was also reported that an increase in die temperature reduces the friction in the press channel of the mill and lowers the energy demand.

From Risø DTU's experience, wood pelletizing normally stabilized at a die temperature of 100-120 ˚C in the bench-scale commercial pelletizers; while this temperature could be much higher (up to 200 ˚C) when pelletizing torrefied wood [4]. Too high temperature results in fire hazard, as pellets start to burn right after leaving the pelletizer. A possible solution is to use lubricant.

1.1.1.4. Press channel dimensions

The press channel length and the ratio between length and diameter, which is known as the compression ratio or aspect ratio, is the most important factor influencing the pressure built up in the press channel of a pellet press. It was reported that an increase in press channel length resulted in higher mechanical properties of the pellets for cattle feed pellets [6]. For wood pellet production, the aspect ratio is usually around 6, while it can be up to 11 – 12 in the case of wheat straw pellets [2].

Previous studies done in Risø DTU showed that the necessary pelletizing pressure increase exponentially for wood species as a function of the increased compression ratio [7]. It means increased channel length (pellet length) or decreased pellet radius result in increased necessary pelletizing pressure.

1.1.1.5. Pelletizing pressure

The pressure typically used in most studies was above 50 MPa, the mechanical properties, compressive strength, and durability improve with an increase in pressure and follow a saturation curve with the plant cell wall density as an upper limit. But there is a certain threshold of pressure and above this pressure, additional energy put into the process is mainly converted into excess heat, rather than contributing to better pellet quality [2].

However, in real production it is difficult to control the pelletizing pressure. Risø DTU's previous work using a bench-scale pelletizer [7] concluded that for every different biomass material, the necessary pelletizing pressure depends upon the material-specific elastic properties, the friction, and the press channel dimensions. Hence, the optimal pelletizing conditions for each material can be achieved by optimizing the press channel dimensions or by changing the friction, e.g. by adding lubricant. On the other hand, the static friction detected during single pellet press tests can therefore be used as an indicator to estimate the relative easiness of pelletizing in the bench-scale pelletizer for different kinds of biomass.

1.1.3. Pelletizing target species

Poplar was pelletized by Mediavillar et al.[8] using a flat die type Amandus Kahl 33-500 pellet press with hole diameter of 6 mm and driving power of 30 kW. The results showed that poplar is a tough material to pelletize and additives are needed. A high quantity of water was necessary to be added (26 – 28%) without additive. However, during the test the pellet press worked in an unstable way with power peaks, vibration and powder production. A more stable operation and lower energy demand was achieved by adding maize starch and/or lignosulphonate. Pelletization with maize starch required moisture content between 12.5 and 13.0% by weight (w.b.) whereas pelletization with lignosulphonate needs values between 9.0 and 10.5%. The optimal pelletization conditions were concluded as: milling particle size below 4 mm, die length 26 mm and 4 wt% (d.b.) of dry additive.

Sorghum stalk was pelletized by Theerarattananoon et al. [9] using a 22.1 kW ring-die pellet mill with 1.5 ton capacity (CPM Master model series 2000, California Pellet Mill Co.). The durability increased initially with moisture and reached a maximum value of 89.5% at 14% to 16% (d.b.) moisture content. Use of a larger hammer mill screen size (from 3.2 mm to 6.5 mm screen openings) resulted in increases of density and durability of pellets, but not in significant levels. Use of a thicker die size (from 4.0×31.8 mm to 6.4×44.5 mm, hole diameter × effective thickness) resulted in significant increase of density and durability of pellets.

Alfalfa was pelletized by Tabil [10] using a CPM CL-5 ring die pellet mill with two different die dimensions (7.8×33.0 mm, and 6.1×44.6 mm). It was found that high die l/d ratio increased pellet durability; hammer mill screen size of 2.4 mm produced more durable pellets than did the 3.2 mm; a conditioning temperature of 92 ˚C and above and 1.5 to 2.5 percentage points of moisture added were optimal for pelleting. Among the five binders tested, hydrated lime and pea starch were found to be the most promising.

1.2. Briquetting

1.2.1. Introduction

Generally there are 3 types of briquetting presses: mechanical presses, hydraulic presses, and screw presses.

Mechanical presses are typically used for large-scale installations from some 200 up to 1800 kg h^{-1} for single line installations, but in principle 2 or more presses can be arranged in groups to establish production centers for several tons per hour. A mechanical press is designed as an eccentric press. A continuously rotating eccentric shaft connected to a plunger presses the raw material through a conic die, as shown in Figure 1. In mechanical presses the counter pressure required can only be adjusted by installing a die with a different conicity or different length. C.F.Nielsen (CFN) market a wide assortment of different dies developed for different woods, agricultural biomass and briquette qualities. Adjustable dies that can be mechanically or hydraulically adjusted are also available. As the mechanical press is driven by an electric motor instead of a hydraulic motor, energy loss in the unit is very moderate and the output in relation to power consumption is thus optimized. The operating life of a mechanical press is considerably longer than for a hydraulic press. In the long run the mechanical press gives a much better return on investment than does a hydraulic press.

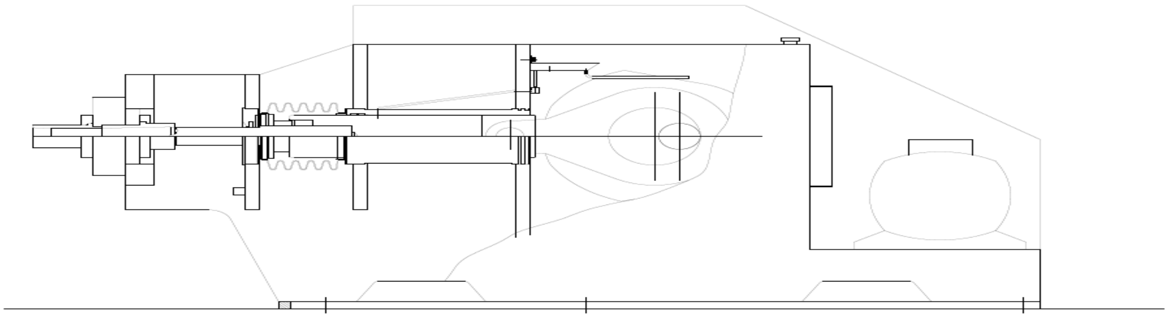

Figure 1 : Sketch of a mechanical press

Hydraulic presses can be divided into two main groups: The low-priced, complete briquetting systems with capacities ranging from 50 to 200 kg h^{-1} and usually producing round briquettes. Such systems are used for small-scale briquetting and preferably only for max. 7 operating hours per day. In addition to these systems there are the professional systems with a capacity of 400 - 1500 kg h^{-1} and mostly for production of rectangular briquettes. These systems are built for continuous operation. Due to size of the briquettes, these are normally sold only for consumer use. In the hydraulic press, the required pressure is produced by the hydraulic system. The specially designed hydraulic cylinder assembly makes the main cylinder release the compressed briquette once the required pressure is reached. The pressure can normally be adjusted via a regulator, meaning that all briquettes are compressed under the same pressure.

A screw type briquette press can produce biomass briquettes with very high compaction, but it also has a very high energy consumption for the process compared to mechanical presses. After feeding, the material is conveyed to the briquette forming head by a revolving screw shaft driven by electrical motor. The screw shaft is the main part of biomass briquette press. The screw distance become smaller and smaller along the screw shaft to briquette forming head. With the decreasing screw distance, the material endures bigger and bigger pressure. Because of the shaft, there is a hole left in the center of biomass briquette column. Screw presses are usually available with capacity from 75 to 250 kg h^{-1}. Because of the high friction the mechanical wear on the screw press is considerably higher than known for hydraulic and especially mechanical presses.

1.2.2. Key process parameters

1.1.1.1. Particle size

In general, the finer the feedstock grinds, the higher the durability. Tabil and Sokhansanj [11] considered particles below 0.4 mm are fine and highly compressible. Large particles are fissure points that cause cracks and fractures in compacts. Several researches reported that mixture of different particle sizes result in better quality due to bonding with no interparticle space [1].

CFN experienced that especially for briquettes with larger diameters 75, 90 mm and higher it is important that there is a mix of different particle sizes in order to produce a high quality briquette. Generally, briquetting can be made with bigger particles than pelletization – up to 20-30 mm – depending on type of raw material, which will generate considerable savings in power costs due to lower hammer mill costs.

1.2.2.1. Moisture content

Several researches recommended a range of moisture content for pelletizing or briquetting of different feedstock: about 10% for switchgrass [12], about 8-9% for alfalfa [5], 6-12% for wood [13]. O'Dogherty [14] concluded that the most important property of straw affecting compression is its moisture content. There is an exponential reduction in relaxed briquette density as moisture content increases. There is an upper limit of moisture content, above which it is impossible to form a briquette of a specified density. The durability of briquettes was high between moisture contents from 13 to 17% (w.b.), and a coherent straw (and lucerne) briquette could not be formed at moisture contents (w.b.) greater than 35%.

It is CFN's experience that the optimum moisture for briquette production varies from one raw material to another. In order to produce a briquette with high quality and density the moisture content will normally have to be between 8 and 12% moisture, whereas briquettes with lower quality – densities below 1.0 ton m^{-3}, can normally be produced with moisture between 6 and 16%. Very few raw materials can be briquetted with moisture above 18%.

1.2.2.2. Die temperature

Demirbas and Sahin [15] used a lab scale hydraulic press, with a punch and die set (25 ×60 mm, or 13 × 40 mm) for 1 – 30 min under pressures of 300 -800 MPa. It was found briquetting wheat straw was very difficult at ambient temperature, and the stability of straw briquettes was increased at temperature above 77 ˚C during compression. Wax was suggested to be responsible for this phenomenon, because of its melting and subsequent solidification provided adhesion between individual fibers.

It needs to be noticed that a mechanical press works differently than a hydraulic press. The dies are pre-heated to approx. 100 ˚C to decrease start-up friction in the system. During operation CFN's presses work with approx. 270 revolutions per minute creating small steam explosions, which heats the biomass and releases lignin that helps create a binding effect. The heating of the dies can be regulated to fit the biomass and the mechanical presses are also able to work with preheated biomass.

1.2.2.3. Die pressure

The effect of die pressure on the briquettes quality was studied by Chin and Siddiqui [16] using a manually operated piston and die press with an internal diameter of 30 mm. It was generally found that as die pressure and dwell time increased, the quality of briquettes improved. The relaxation in length of most biomass materials decreased with dwell time until an optimum value was reached. Also, as the die pressure increased, the relaxation in briquettes was reduced.

However, due to the working principle of a mechanical press, the real process is very hard to be replicated in a lab-scale test setup. The accumulating heat, coming from the kinetic energy being transferred by the plunger's impact, and alternating extreme pressure and pressure drop (when the plunger retracts), causes the moisture inside the cellular structure of the biomass to expand rapidly, thus effectively opening the structure and making the lignin more easily available to act as a bonding agent in the densification. This part of the process is not as simple as a lab-scale test setup, and it's the primary reason that tests at larger scale are necessary. Therefore CFN requires larger quantities (preferably above 200 kg) for testing on their industry-scale test-machine.

1.2.3. Briquetting target species

Willow briquettes have been reported [17] to be successfully manufactured by a commercial briquetting system using hydraulic screw presses. The willow briquettes had a density of 1160 kg m^{-3} and an energy value of 19.5 MJ kg^{-1}.

Sorghum and *miscanthus* [18] have been also found as two good pressing crops at moisture contents of 10.95% and 9.97% respectively, by using a hydraulic commercial briquetting press (HLS 50 of Briklis Ltd.) with a diameter of about 65 mm. The densities of these two kinds of briquettes were 810 – 870 kg m^{-3} for sorghum, and 750 – 850 kg m^{-3} for miscanthus.

Triticale straw chopped at different lengths (20, 30, 40, 50 mm) was briquetted using a screw type briquetting press 'Biomasser BSO6' with capacity of 40 – 50 kg h^{-1} (4.2 kW electric motor) [19]. The briquetting was carried out at operating temperature of the press cylinder 270 ˚C and with a cooler–stabilizer – 5500 mm long. The diameter of briquettes was 76 mm. The moisture content of chopped straw was 10.54±0.22%. The highest density (747±4.8 kg m^{-3}) and stability of the dimensions were typical for the briquettes formed from mixture of straw chaff at 20 and 50 mm long.

CFN has experience with briquetting miscanthus and triticale straw. For both raw materials the optimum particle size has been between 15 and 20 mm, and the moisture approx. 10-12%. Briquettes have been produced in 60, 75 and 90 mm with specific densities ranging from 900-1200 kg m^{-3}.

1.3. Additives

According to EN 14961-2, additives are allowed to a maximum of 2% of the total mass of the pellets. The amount of additives in production must be limited to 1.8 wt%, the amount of post-production additives (e.g. coating oils) must be limited to 0.2 wt% of the pellets. Additives, such as starch, corn flour, potato flour, vegetable oil, lignin from sulphate kraft process etc., must originate from processed or unaltered farming and foresting products.

Tarasov et al. [20] reviewed the effect of different additives on wood pellets' characteristics. All types of starch (native wheat starch, oxidized corn starch, native potato starch, and oxidized potato starch) increased the mechanical durability of the wood pellets, with the best results for mechanical durability obtained by adding oxidized corn starch. Starch additives also reduced the final moisture content more than lignosulphonate additives. Lignosulphonate additives result in the best mechanical durability values for wood pellets, but significantly increased sodium and sulphur content and consequently increased SO_x emissions during combustion. Motor and vegetable oil additives increased the calorific value minimally but significantly increased CO emission. Corn starch and dolomite additives also significantly increased CO emission.

There is limited information on the effect of additives on the properties of straw briquettes. Typical materials are lignosulphonates, ammonium and sodium hydroxides and starch based products. It was found that adding up to 5% by weight of additives to ground and chopped straw resulted in packages of good durability [14].

CFN's experience with additives is limited, as most briquettes were made without additives. Some wood based raw materials especially pine, require additives such as lignosulphonate, which results in higher density and lower power consumption. For agro based raw materials calcium has been a good additive to obtain higher density. Lignosulphonate is also a good additive in relation to some agro based raw materials.

2. Experimental plan

2.1. Pelletizing

In the experimental part of LogistEC, pelletizing properties of nine biomass species (triticale, miscanthus, willow, eucalyptus, poplar, giant reed, tall fescue, alfalfa, sorghum) will first be tested in a single pellet press. The single pellet press was invented and constructed at Risø DTU. The diameter of the press channel is 8 mm, the temperature of the die is controlled using a thermo-couple connected to a control unit. Based on the literature, the following pelletizing conditions were selected and are being planned: die temperature at 60, 90, 120 ˚C, pelletizing pressure at 200 MPa and holding time for 10 s, particle size of < 2.8 mm, moisture contents for willow and eucalyptus are 5-10%, for poplar is 26-28%, for triticale straw, giant reed grass, miscanthus grass, and tall fescue are 10-20%, for sorghum stalk and miscanthus grass are 10-16%, for alfalfa is 8-9%.

All nine biomass species will be tested according to the tests mentioned above, and the crops that appear unsuitable for pelletizing will not be evaluated further. For the suitable feedstock, the pelletizing conditions will be optimized with regard to pressure, die temperature, moisture content, and additive. Additives that are planned to be tested are starch, lignin by product of pulp production, and sodium hydroxide.

Subsequently the optimized parameters will be used to adjust the settings of a bench scale pelletizer, which is a ring die pellet mill (15 kg h^{-1}, California Pellet Mill Co.). It is equipped with a data-logger ammeter of the pellet mill motor functioning as a load indicator. A stationary knife mounted next to the matrix cuts the pellets after the extrusion. There are several sets of ring dies with different compression ratios, and each die has 40 holes. The quality of produced pellets i.e. strength, durability and density will be investigated by standard protocols.

The outcome of this part of work is first a series of optimized pelletizing parameters for each specific biomass, and later a comparison of the briquetting technology and the conventional pelletization technologies, for both woody and grassy energy crops. The work of pelletizing torrefied and torwashed biomass will be described and carried out in 'D3.5-Improved densification recipes for thermally pre-treated energy crops'.

2.2. Briquetting

After the bench scale pelletizing tests, the optimal settings (die temperature, moisture content, and additive) will be used and adjusted for lab scale briquetting tests at CFN. All tests will be performed on an industrial briquetting press. Normally, tests are performed in larger diameters such as 75 and 90 mm, but for LogistEC tests a 50 mm die system will be used. The briquetting press will be a BP6500, which normally can produce up to 1.3 to 1.8 tons per hour, but for the LogistEC tests the average capacity is estimated to be approx. 350 kg per hour. Alternatively, the tests will be made on a BP2000 laboratory press with 40 mm die system, with a capacity of approx. 150 kg per hour.

The following raw materials: triticale, miscanthus, willow, eucalyptus, poplar, giant reed, alfalfa, sorghum will be tested at normal natural condition on the laboratory press. In addition, based on small scale results, ECN will scale up one or two types of biomass, and will produce sufficient material for briquetting tests by CFN.

The set-up of the press die will be as follows, and the cooling line will be 6 m:

- Main die nominal 40 mm diameter – length 150 mm

- Extension die nominal 40 mm – 200 and 400 mm – retention time in die system is expected to be respectively 10 and 16 s
- Pressure will vary from raw material type to raw material type as conical dies are optimized for the raw material
- Temperature of the die system will be set at approx. 250 °C – for torrefied wood tests

In connection with the tests following data will be collected:

- Raw material type
- Moisture content
- Particle size
- Bulk density of raw material
- Types of dies used
- Die temperatures
- Power consumption
- Additives
- Capacities
- Density of briquettes
- Durability tests
- Briquette description – surface, appearance etc
- General conclusion

For torrefied wood following additional data will be collected:

- Data from the torrefaction process – temperature, retention time etc
- HHV of the raw material
- Water absorption tests

This work will be carried out by CFN to determine which modifications are needed to optimize the briquetting equipment as well as briquetting conditions, before performing the actual demonstration of the optimized briquetting process, which is to take place in WP5.

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