REPORT

Data til dimensionering af NOWEAR neddeler

EUDP 14-1 / 64014-0136

February 2015

TK Energy ApS

1. Preface

This document is the final report of the project EUDP 14-1, Data til dimensionering af NOWEAR neddeler (j. nr. 64014-0136).

2. Table of contents

3. Introduction

This report is the final report of the project EUDP 14-1, Data til dimensionering af NOWEAR neddeler (j. nr. 64014-0136). The project is conducted by TK Energy ApS, who acknowledge the support from the EUDP.

The purpose of the project was to obtain the foundation for dimensioning of a NOWEAR downsizer for downsizing of biomass. The NOWEAR downsizer is an inertia mill, where biomass is downsized by one high velocity impact. The project has focused on establishing correlations between downsizing, temperature, moisture and velocity of the impact.

The project started with a study of particle characterization in order to be able to measure the relevant information of the downsized biomass and to secure that an objective evaluation of the downsized biomass was possible.

Parallel with the study on particle characterization a test facility for downsizing biomass was constructed. A number of experiments were conducted and the effects of temperature, moisture and impact velocity on the downsizing were examined.

During the project the test facility has been presented to several potential customers that have shown a high interest in the downsizer.
The planned publication in Ingeniøren has not been conducted as the focus has been on the commercial presentations.

4. Presentation of the project

4.1. Background

This project has been initiated by the collaboration between TK Energy and Jean-Marie Seiler, Research Director at the CEA (French Atomic Energy and Alternative Energies Commission).

The interest of developing a downsizer where particles are hit only one time has been discussed and evaluated. An evaluation note on grinding energy, written by Jean-Marie Seiler, is attached to this report (cf. Appendix 1). The document calculates the theoretical energy required by a downsizer for hitting particles only one time and compares it to the energy consumption of traditional downsizers where the particles have to be hit several times in order to reach the target size.

The conclusion that can be taken from this calculation is that the energy consumption for downsizing biomass with the technology tested in this project is much lower than with traditional mills. Developing a single impact downsizer could lead to an energy consumption 10 times lower.

4.2. Experimental facility

4.2.1. Description

For this project, an experimental facility has been built and is divided in 3 main parts:

- a feeding bin
- a wood chipper
- a particle collecting system

Feeding bin

A feeding bin, with a volume of 100 L, is placed at the top of the facility. The bin is equipped with a top flange, for filling the biomass in, as well as a rotating mixer that ensures the material to fall into the feeding screw. This screw, placed at the bottom of the bin, transports the material into a vertical pipe with a biomass flow rate of approximately 0.25 m^3/h.

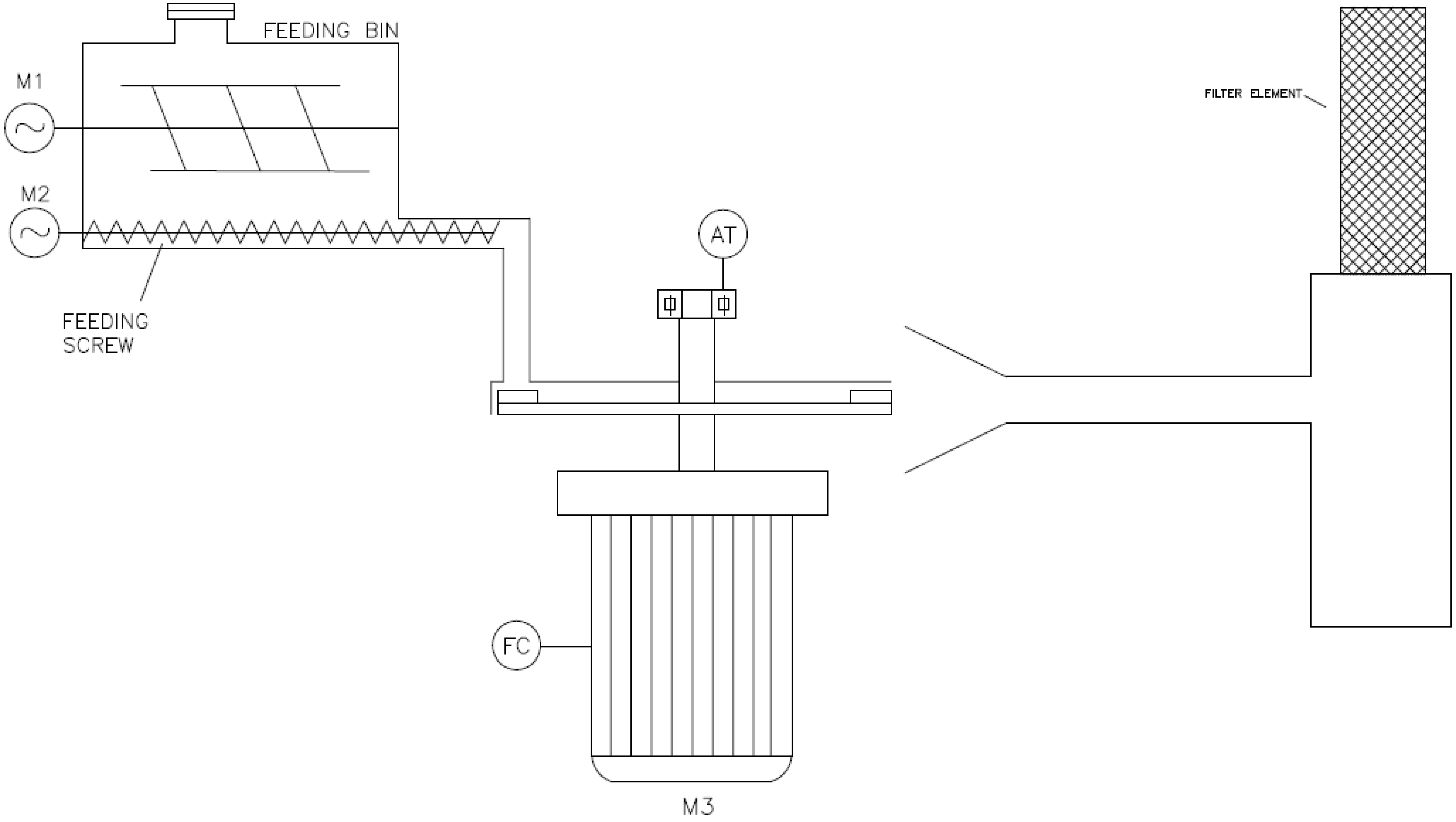
Chipper

The wood chipper is basically a horizontal disc (~Ø1m) on which are mounted 4 hammers (30 mm x 30 mm x 100 mm) to chop the material. The disc is driven by a 75 kW asynchronous motor. The velocity of the disc can be adjusted thanks to a frequency controller.

Particle collecting system

A funnel guides the flow of crushed particles into a vertical cylinder. A filter element, made of fabric and placed on the top of the cylinder, keeps the particles inside the cylinder and let the flow of air going through.

The diagram next page shows the principle of the facility.



M -> MOTOR
FC -> FREQUENCY CONTROLLER
AT -> ACCELOROMETER TRANSMITTER

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TK Energy ApS	EUDP NOWEAR	
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Figure 2. Pictures of the facility

4.2.2. Technical data

- Dimensions of hammers: height 30 mm - width 30 mm - length 100 mm
- Number of hammers: 4
- Dimensions of the disc: Ø 985 mm - thickness 30 mm
- Shaft: Ø 110 mm
- Bearing SKF - SNL 519-516 - Ø70
- Motor: 75 kW / 2970 rpm
- Frequency converter: DANFOSS 131F0445 – 75 kW

4.2.3. Balancing of the disc

After manufacturing of the disc, some measurement controls have been done. The disc is not perfectly round because of the tolerance of the machine. As shown on the sketch hereunder, an extra layer of 0.1 mm on the diameter has been measured on one side of the disc.

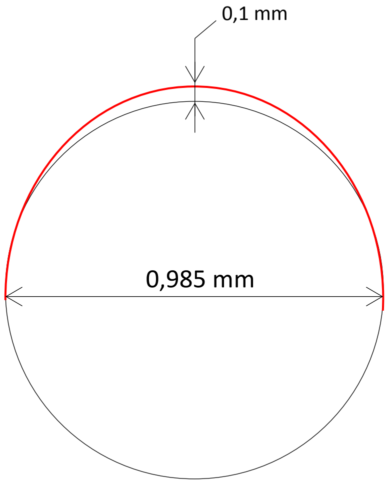


Figure 3. Disc machined

To facilitate the calculation, this extra layer is considered to be equivalent to a semi-circle layer of thickness 0.05 mm:

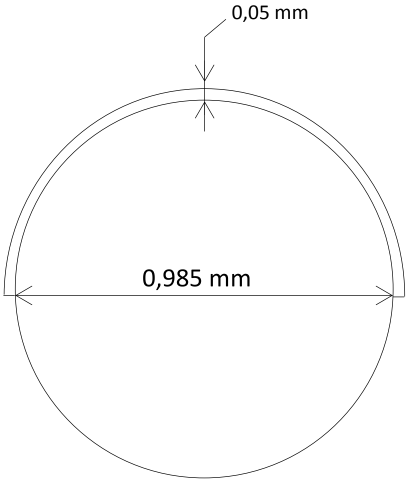


Figure 4. Disc: hypothesis of unbalancing

From this hypothesis, the weight of this layer can be estimated to:

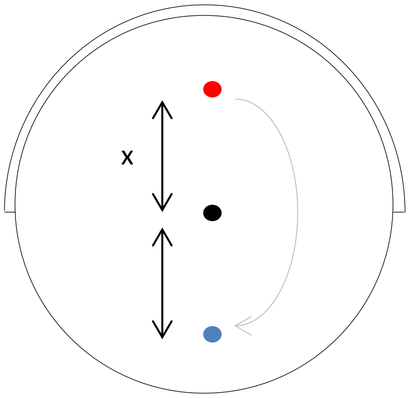
$$\text{Extra layer weight m} = \rho_{\text{steel}} \times V_{\text{layer}} = \rho_{\text{steel}} \times \text{thickness disc } \times \text{area layer}$$

$$\mathrm{m} = 7850 \times 0{,}03 \times \pi \times \frac{(0{,}985/2 + 0{,}05)^2 - (0{,}985/2)^2}{2}$$

$$\mathbf{m = 36,4\ g}$$

The distance between the centre of gravity of this layer and the centre of the disc is as follows:

$$x = \frac{2R}{\pi} = \frac{2 \times (0{,}985 + 0{,}05)/2}{\pi} = 313{,}5\ \mathrm{mm}$$



Red point: centre of gravity of the extra layer

Black point: centre of the disc

Blue point: position of the balancing weight

Figure 5. Disc balancing

In order to have a perfectly balanced system (centre of gravity matching with the centre of the disc), a weight equivalent of the extra layer (m=36.4 g) should be placed on the opposite side at the same distance “x” from the centre of the disc (blue point).

Considering the speed and inertia of the chipper, the balancing of the system is judged as a critical element. In this way, the frame of the mill has deliberately not been oversized in order to ease the detection of potential shakiness. A pre-test has been conducted to evaluate the vibration level and is presented in part *6.1. Pre-tests*.

4.2.4. Fastening of the hammers

Another point that has been carefully looked at is the sizing of the bolts fastening the hammers to the disc.

The peripheral velocity where the hammers are located can be up to 250 m/s. The bolt size has been chosen in order to avoid any risk of breaking caused by the centrifugal force.

First, the force applied by the hammer to the bolts has been calculated:

Hammer	Weight hammer	0,53	kg	[steel density x length x height x width]
	Radius of the hammers locations	442,5	mm	
	Hammer speed	250	m/s	
	Hammer angular velocity	564,97	rad/s	[speed / radius]
	Acceleration of the hammer	1,41E+05	m/s^2	[radius x angular speed^2]
	Force applied by the hammer	**74,86**	**kN**	[acceleration x weight]

Then, the shear strength of 2 bolts M12 grade 12.9 has been calculated and compared to the force applied by the hammers:

Bolts	Bolt yield strength Re	1080	Mpa	grade 12.9 -> [12 x 9 x 10]
	Shear yield strength Reg	864	MPa	[0,8 x Re]
	Bolt section area A	157,0	mm^2	
	Shear yield strength for 1 bolt	135,6	kN	[Reg x A]
	Shear yield strength for 2 bolts	**271,30**	**kN**	[2 x Reg x A]
	Safety factor	**3,6**		[shear yield strength / force applied by the hammer to the bolts]

The safety factor between the bolts shear strength and the force applied is large enough to ensure that the bolts will not be damaged by the hammers force at maximal speed.
This raw calculation does not take into account that each hammer has actually been mounted into a groove of 5 mm depth, machined in the disc. This assembly distributes some of the force to the disc and reduces the shear force applied to the bolts. It can be considered that the force generated by the wood to the hammers will be then taken by the disc.

For more safety the facility is placed anyway in a closed room, built with reinforced concrete walls, and is remote-controlled from the outside of the room to prevent any accident.

4.2.5. Hammers

The project has not focused on the design of the hammers at this stage of the development and therefore the hammers have a simple rectangular parallelepiped shape (30 mm x 30 mm x 100 mm). Consequently, a large quantity of air is moved by the hammers resulting in high power consumption at high speed (cf. part *6.4.1. Power consumption*).
This project focuses on studying the impact of hitting particles once by the hammers. The shape and dimensions of the hammers chosen ensure that the particles will be easily hit. In a further step of development, it will be however essential to find an optimal hammer design regarding aerodynamics and so energy consumption.

The hammers have been deliberately made of soft steel (S235) in order to observe potential wear and damages. A visual inspection has been done during and after the experimental stage; the results are presented in part *6.4.8 Wear of the hammers.*

4.3. Parameters of the experiments

The test facility built in the frame of this project has the purpose to demonstrate the efficiency of the technology and to study the effect of different parameter on the downsized biomass. Indeed, one of the main interests of this project is to determine what parameters can influence the produced powder and how.

Therefore the following parameters have been tested:

- Change of material : wood chips / wood pellets
- Change of speed of the mill : 30 m/s to 200 m/s
- Change of moisture : 5% moisture / 30% moisture / 60% moisture
- Change of the temperature of the material: ambient / 150°C

- Change of the number of recirculations of the material: 0 to 2

The results are presented and discussed later in this report (cf. Part *6.4. Results and interpretation*).

4.4. Particle analysis

In order to analyse and compare the obtained biomass powders, TK Energy has been through a phase of definition of the instrumentation needed to characterize and compare the downsized test samples. This chapter describes briefly what technologies have been chosen for the particle characterization and the reasons.

4.4.1. Relevant data

Particle characterization has a wide field and can easily give hundreds of data from one powder, but considering all of them can become confusing. Therefore, this part explains what data will be focused on and why.

The downsizer developed in this project is intended to be used as a fuel preparation step for the combustion or the gasification industry. In these kinds of processes, the most important criterion is the reactivity of the fuel in order to have a short residence time in the burner or gasifier.

The reactivity depends mainly on the heat transfer between the gas and the particles. This heat transfer is influenced by the distance between the perimeter of the particle and its centre but also by the heat exchange surface area.

Based on these facts, the most relevant data to analyse are expected to be:

- Size

One of the most important information is about particle size, for instance particle size distribution or smallest particle dimension. Particle size is largely linked to reactivity and influence significantly the residence time of a fuel in a process; it is essential to know the performance of the downsizer on this point.
Size analysis is essential in order to study the direct correlation between downsizer settings and size of particles.

- Shape

Shape analysis is relevant to couple with particle size analysis. Geometry of the particle, as roundness or aspect ratio, affects also reactivity because it directly influences the heat exchange. For instance, a long and thin particle will reacts faster than a spherical particle of same volume. Alone, a particle size analysis will not give this kind of information and would be incomplete.
So then, shape factors are interesting to look at and evaluate if they are controllable by some of the downsizer parameters.

- Surface

Information on the surface of particles is pertinent as well. Indeed, it could be interesting to complete size and shape data with porosity or surface area of particles. These parameters also influence the reactivity between biomass particles and gas. The way of downsizing the biomass could very well modify these parameters.

These 3 types of data are relevant to look at in this project. The choice of the technology selected for this particle analysis is argued hereunder.

4.4.2. Technology

Particle characterization could have been avoided by the use of a drop tube furnace. This technology can analyse the conversion rate of biomass particles in combustion or gasification conditions. In this way, the fuel reactivity is directly measured and particle analysis is not indispensable anymore. Drop tube furnace would have been the best analytical instrument to couple with the downsizer but the cost and the time to set up such an instrument are not compatible with the resources of this project. Consequently, it has been removed from the options to consider.

Hereafter is a listing of equipment that could fit with our need and technical specifications:

- Sieve shakers

Sieving machines are the simplest way to measure particle size distribution of a powder. The operator uncertainty is low and the complexity of a statistical software analysis is avoided. Companies working with biomass keep using sieve shakers even if they also own the most advanced technologies of size characterization.

The only issue of sieve shakers is in case of particles with a third dimension longer than its two first dimensions. These particles could go through a smaller sieve than the third dimension of the particle.

- Picture

Another simple way of characterizing particles is a microscope or camera. From this kind of instrument, observation on the shape of particles can be made. It is a pertinent tool to compare shape properties between different powders.
Several manufacturers have also developed software that can give statistical results from the pictures. Nonetheless, the feedback from experienced people in this domain is quite negative, mainly due to the small size sample on which are based the calculations.
There are two main problems of using a microscope. First, it requires preparing the sample by diluting particles and putting some of the solution on the microscope slide. This wet way of preparing the sample is not suitable with biomass particles because of the risk of agglomeration between particles and the hydrophilic property of most of biomasses. The use of a microscope is subject to find a dry sample preparation method.
The second downside of microscopes is their short depth of field, making them suitable for observation of “flat” samples, which is not the case of biomass particles.

- Laser analyser

Laser diffraction is one of the most used technologies for particle size characterization when dry analysis is requested. A large sample can be analysed automatically by the instrument (pneumatic injection), that use the principle of laser diffraction to measure the size of the particles.
Some laser particle analysers have a high-speed camera integrated in order to get information on the shape of the particles.
The downside of laser diffraction analysis is its low accuracy with non-spherical particles. Biomass particles have usually not spherical shape.

- Camsizer®

The Camsizer® is based on a dual-camera technology. This image processing instrument can determine many parameters of size and shape by taking a picture of each particle.
Although it seems more reliable than laser diffraction for biomass particles, the feedback from Camsizer® users is that the high number of output data is often confusing and it is difficult to determine what data are really relevant.
Several industrial partners of TK Energy have a Camsizer® and it could be an asset to show results that potential customers are familiar with.

- BET surface analyser

Some surface structure of the particles can be observed by optical way, but it is difficult to quantify the surface area or porosity with this kind of technology. However, the BET analysis method is more common and more reliable to measure these two parameters. The measurement principle is based on the link between gas adsorption on the particles surface and partial pressure of the adsorbate gas.

On the downside, it is difficult to directly link the BET area to the reactivity but a strong correlation between conversion rate of the biomass particles and adsorption is expected, as the conversion of biomass requires reaction between the particles and the gas.

For our application, such an instrument could be complementary with size and shape analysis.

Based on this overview of the different particle analysis technologies, it has been concluded that:

- A sieve shaker will be used in this project as a simple and reliable way to analyse particle size distribution. Sieves match international standards and the method is well defined. This analyser will give the particle size distribution of the different powders produced by the downsizer. It is acknowledged that the sieve shaker will only characterize the two smallest dimensions of the particles and not their length, but the length generally does not affect the particles reactivity.
- A camera equipped with a macro objective will be used to characterize the particles shape. As it is mainly the shape of the fraction larger than 1 mm that is interesting, this equipment is sufficiently good. The microscope has been dismissed because of the wet dilution required and the short depth of field, both inappropriate to biomass particles.
- Laser diffraction systems are not suitable for non-spherical particles and the results from image processing systems are complicated and confusing. BET surface analysis is pertinent but will not be used in this project, as it has been decided to focus on sieve shaking and pictures of particles in a first time.

5. Methodology

5.1. Experiment

The procedure for making an experimental test is the following:

- The material is weighed and put into the feeding bin
- The mixer is started to ensure a good filling of the screw
- The wood chipper is started and set at the requested speed
- When the speed is reached, the feeding screw is started and the material is chopped
- The chipper is kept running until all the material has been chopped (time estimation in function of the volume introduced into the dosing bin) and then stopped
- The particles are removed from the collecting system and weighed

The purpose of weighing the material at the inlet and at the outlet is the making of a mass balance. The mass balance shows the quantity of material that is lost during the experiment and can help to explain some results.

5.2. Particle analysis

From each experiment, a sample is taken from the downsized material for analysis. First, a size distribution analysis is made thanks to a sieve shaker (cf. part *5.2.1. Sieving*). If necessary, some fractions are photographed for shape analysis (cf. point 5.2.2. Shape). For potential further analysis, another sample of each experiment is also saved.

5.2.1. Sieving

For the particle size analysis by sieving, the European standard EN-15149-2:2010: *Solid biofuels - Determination of particle size distribution - Vibrating screen method using sieve apertures of 3,15 mm and below* has been followed. Equipment and procedure are based on this standard.

Hereunder is the detail of the sieving equipment that has been purchased for this project:

- Sieve shaker: FRITSCH Analysette 3
  - Amplitude from 0,1 to 3 mm
  - Programmable sieving time
  - Up to 10 sieves
- Test sieves: RETSCH - Certified in compliance with ISO 3310-1
  - 125 µm woven wire mesh
  - 250 µm woven wire mesh
  - 500 µm woven wire mesh
  - 1,0 mm woven wire mesh
  - 1,4 mm woven wire mesh

  - 2,0 mm woven wire mesh
  - 2,8 mm woven wire mesh
  - 3,15 mm round holes
- Precision balance: VVR - SE 2201 EU
  - 0,1 g accuracy
  - Range: 2200 g

The only deviations from the standard EN 15149-2 are:

- The fractions have been weighed to the nearest 0.1 g. The standard recommends weighing to the nearest 0.01 g. Considering the repeatability of our experiment, weighing more accurately than the nearest 0.1 g is pointless
- An additional 125 µm sieve has been added for more detail in the particle distribution

5.2.2. Shape

In order to observe and compare the shape of particles, a small setup has been made to take pictures of the particles. It includes:

- Reflex camera NIKON D3100
- Macro objective NIKON AF-S DX Micro NIKKOR 40 mm f/2,8G
- Ring flash Aputure HN100
- Camera stand with height adjustment

6. Experiments

This chapter describes the pre-tests, the material used and the experiments that have been conducted. It ends by presenting the results of the experiments and their interpretation.

6.1. Pre-tests

Several pre-tests have been conducted after the manufacturing and assembly of the downsizer.

Test of the mill at different speeds

First, a series of pre-tests has been run idle at different speeds in order to check the good operation of the mill. These tests have shown that the mill is surprisingly stable and the amplitude of vibrations is low.
As a result, it has been decided that the balancing weight was finally not necessary for this prototype. However, a particular attention should be given to the balancing of the mill disc in the construction of the NOWEAR downsizer.

Injection of the material

The second test was focused on the location of the injection of biomass to the downsizer. The feeding bin is fastened to the mill in such a way that the feeding pipe can be moved in different positions.
Two positions were discussed: above the hammer and between the centre of the disc and the hammers.

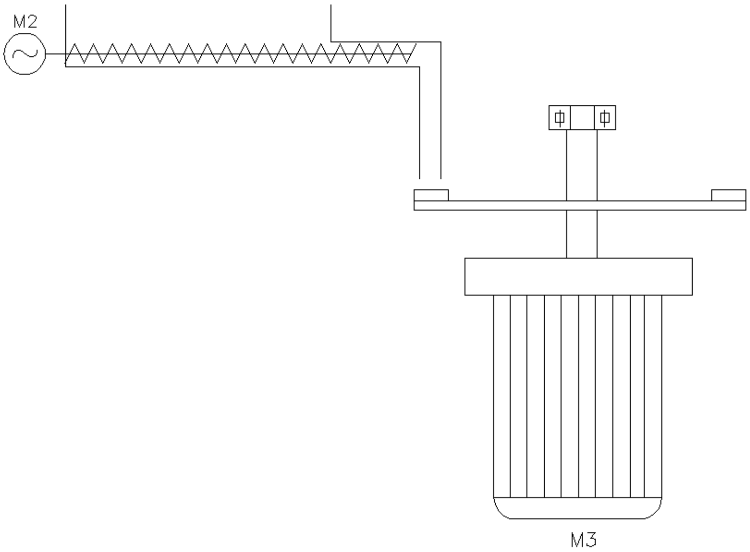


Figure 6. Material injection above the hammers

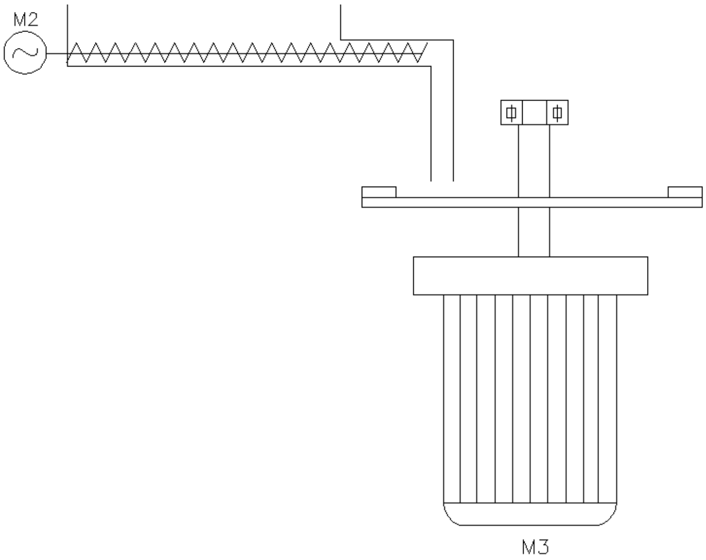


Figure 7. Material injection between the hammers and the centre of the disc

After experimentation, it appears that the injection above the hammers is more efficient. The distance between the end of the injection pipe and the top of the hammers is about 2 mm.

This introduction of the biomass is judged good enough for obtaining usable data but it will have to be improved further in order to get optimal downsizing.

Improvement of chopping

The first operational tests have shown that some of the particles were not hit by the hammers but only blown by the air flow when the mill is running at high speed. To ensure that all particles are hit by the hammers, a thin plate of steel has been mounted 2 mm above the hammers. New tests have demonstrated that the collision between the hammers and the material was improved by this top lid and the chopping efficiency increased.

Particle collecting system

The particle collecting system has been developed in a last stage. It consists in a funnel, a pipe, a collecting bin and a filter element. The pre-tests have leaded to choose the right location of the funnel, to add a collecting bin and choose a suitable filter element.

To evaluate the improvements made, mass balances have been monitored after each pre-test of the collecting system. The final collecting system catches more than 80% of the material during an experiment. The 20% of particles that are not caught are mainly dust particles that go through the filter element. This is assumed by the fact that a lot of dust is found in the room after an experiment. Those particles are so small that they will react very fast in an energy production process and therefore it is not interesting to focus on this fraction here.

6.2. Material

The main material used for the experiments is beech wood chips, which is defined as hard wood. The chips size is few centimetres. Some wood chips can be up to 5 cm long.

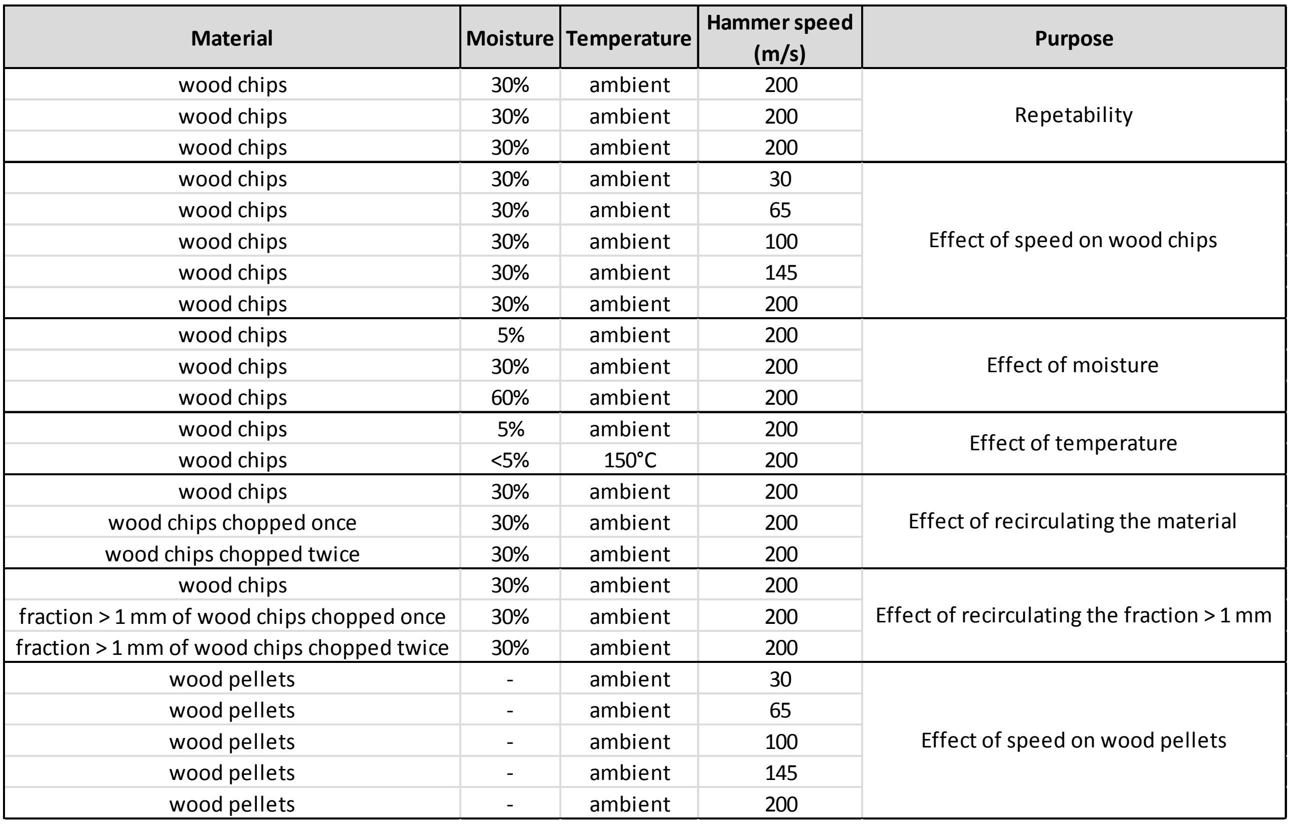
Figure 8. Picture of the beech wood chips used for the experiments

Experiments with wood pellets have also been conducted. The wood pellets used are standard commercial wood pellets of 8 mm from the manufacturer AGROL.

Figure 9. Picture of wood pellets used for the experiments

6.3. Experiments conducted

The following list introduces the experiments that have been conducted. It details the parameters of material, moisture, temperature and hammer speed as well as the purpose for each experiment.



Material	Moisture	Temperature	Hammer speed (m/s)	Purpose
wood chips	30%	ambient	200	Repetability
wood chips	30%	ambient	200	
wood chips	30%	ambient	200	
wood chips	30%	ambient	30	Effect of speed on wood chips
wood chips	30%	ambient	65	
wood chips	30%	ambient	100	
wood chips	30%	ambient	145	
wood chips	30%	ambient	200	
wood chips	5%	ambient	200	Effect of moisture
wood chips	30%	ambient	200	
wood chips	60%	ambient	200	
wood chips	5%	ambient	200	Effect of temperature
wood chips	<5%	150°C	200	
wood chips	30%	ambient	200	Effect of recirculating the material
wood chips chopped once	30%	ambient	200	
wood chips chopped twice	30%	ambient	200	
wood chips	30%	ambient	200	Effect of recirculating the fraction > 1 mm
fraction > 1 mm of wood chips chopped once	30%	ambient	200	
fraction > 1 mm of wood chips chopped twice	30%	ambient	200	
wood pellets	-	ambient	30	Effect of speed on wood pellets
wood pellets	-	ambient	65	
wood pellets	-	ambient	100	
wood pellets	-	ambient	145	
wood pellets	-	ambient	200	

Figure 10. List of the experiments conducted

6.4. Results and interpretation

This chapter presents the results of the different experiment conducted. Each graph is followed by explanations and interpretation of the results.

Note: most of the charts includes a fraction called ”Not caught”. It corresponds to the percentage of particles that has not been caught by the collecting system. As explained before, the hypothesis is that the filter element let some of the thinnest particles going through.

6.4.1. Power consumption

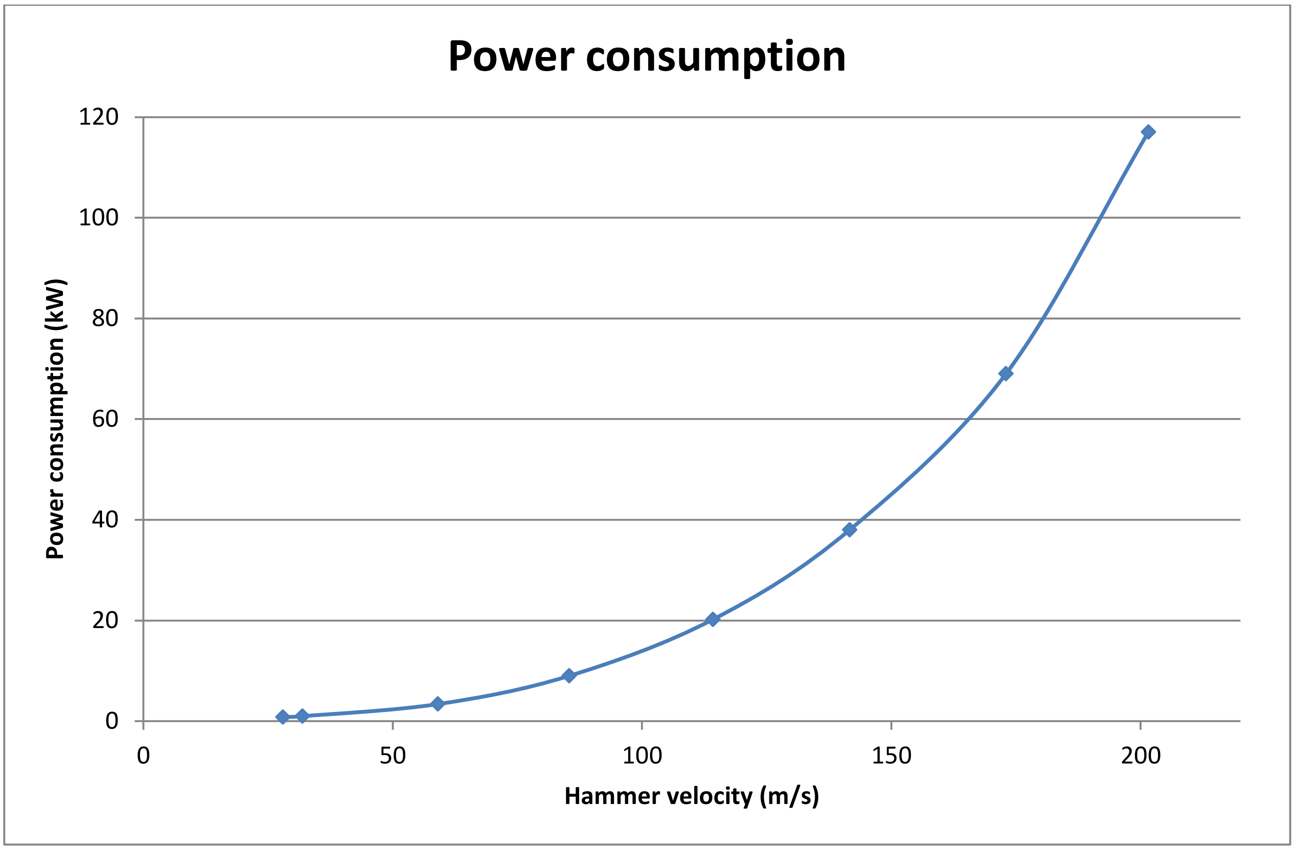


Chart 1. Evolution of the power consumption in function of the hammer velocity

This first graph shows the evolution of the power consumption in function of the velocity of the hammers. The power is measured by the frequency controller in function of the frequency.

This test has been realised without chopping biomass. The extra power consumption induced by the addition of material is so low compared to the energy requested to run the mill that no significative difference has been detected and therefore the power consumption with material is not shown here.

6.4.2. Repeatability

Experimentation has started with tests of repeatability. The repeatability is useful to avoid wrong interpretation of results.

Three tests with the same parameters have been conducted:

- Material: wood chips
- Moisture of the material: 30%
- Ambient temperature
- Speed: 200 m/s

The graph hereunder presents the results of repeatability of the chopping experiment:

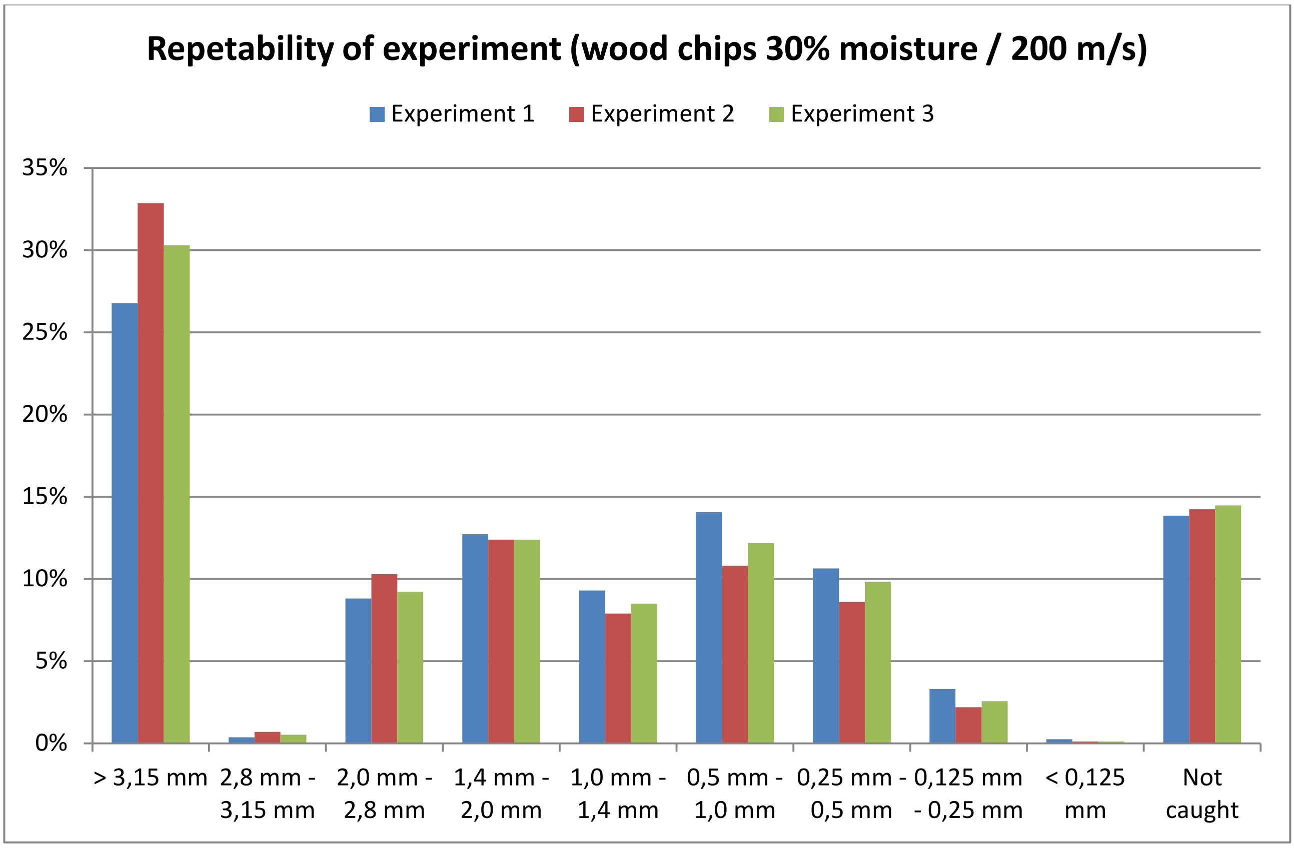


Chart 2. Particle distribution of 3 identical experiments

A maximal deviation of 6% is detected on the largest fraction. The other fractions have a lower variation. We can see that the part lost during the experiment is quite similar in the 3 tests.

Then, the repeatability of the sieving analysis has been tested. Two samples from the same experiment have been analysed with sieving. The sieving parameters were identical for both samples.

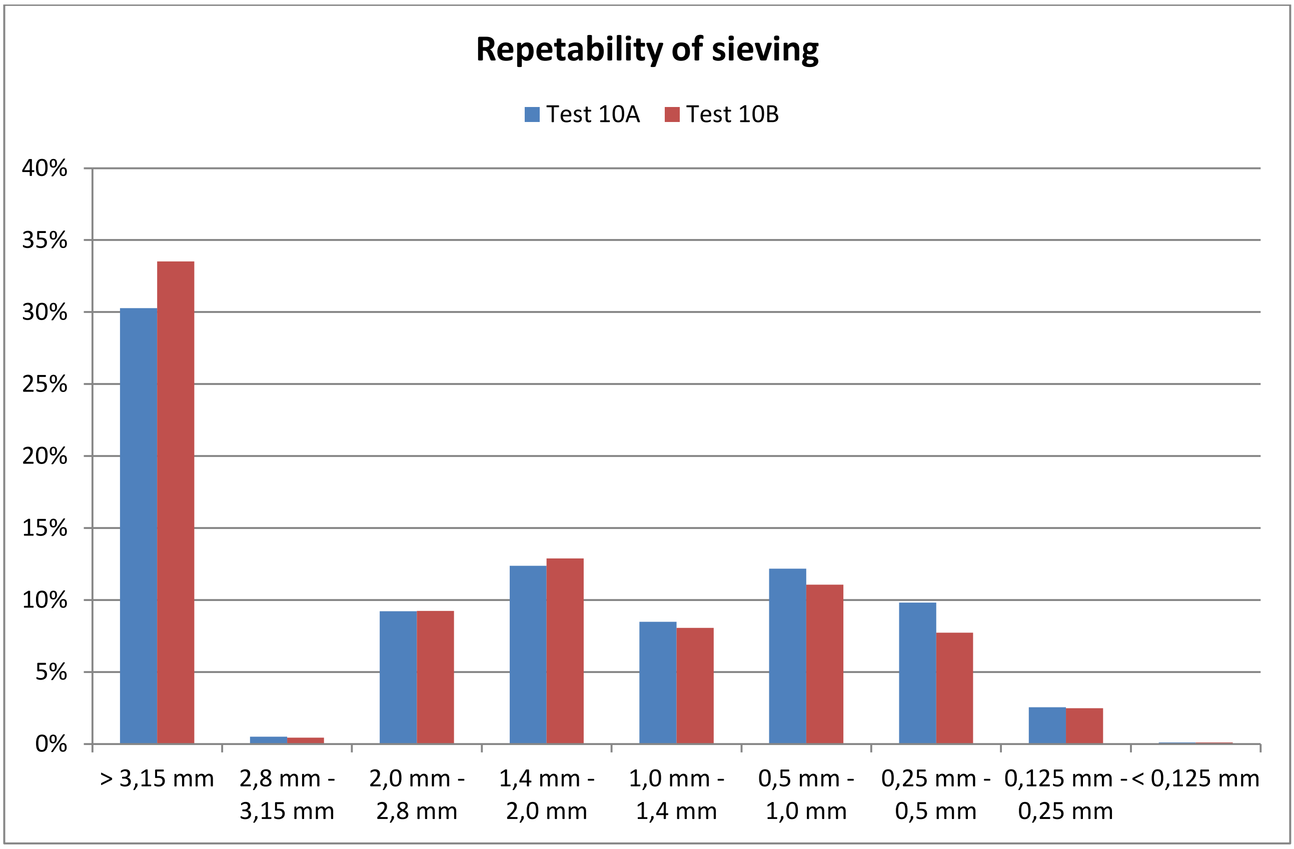


Chart 3. Repeatability of the particle distribution analysis

The maximal deviation between the two sieving is about 3%. This deviation might come mainly from the way the sample is taken from the chopped material. Indeed, the material is not uniform thus it is difficult get two perfectly identical samples.

6.4.3. Effect of speed on wood chips

The velocity of the hammer is expected to be the most important factor in the chopping efficiency. Therefore, it is one of the first experiments that have been conducted. The remote-control system of the frequency controller includes a potentiometer that enables to set the requested frequency. The frequency span used is from 10 to 72 Hz corresponding to a hammer velocity from 30 m/s to 200 m/s.

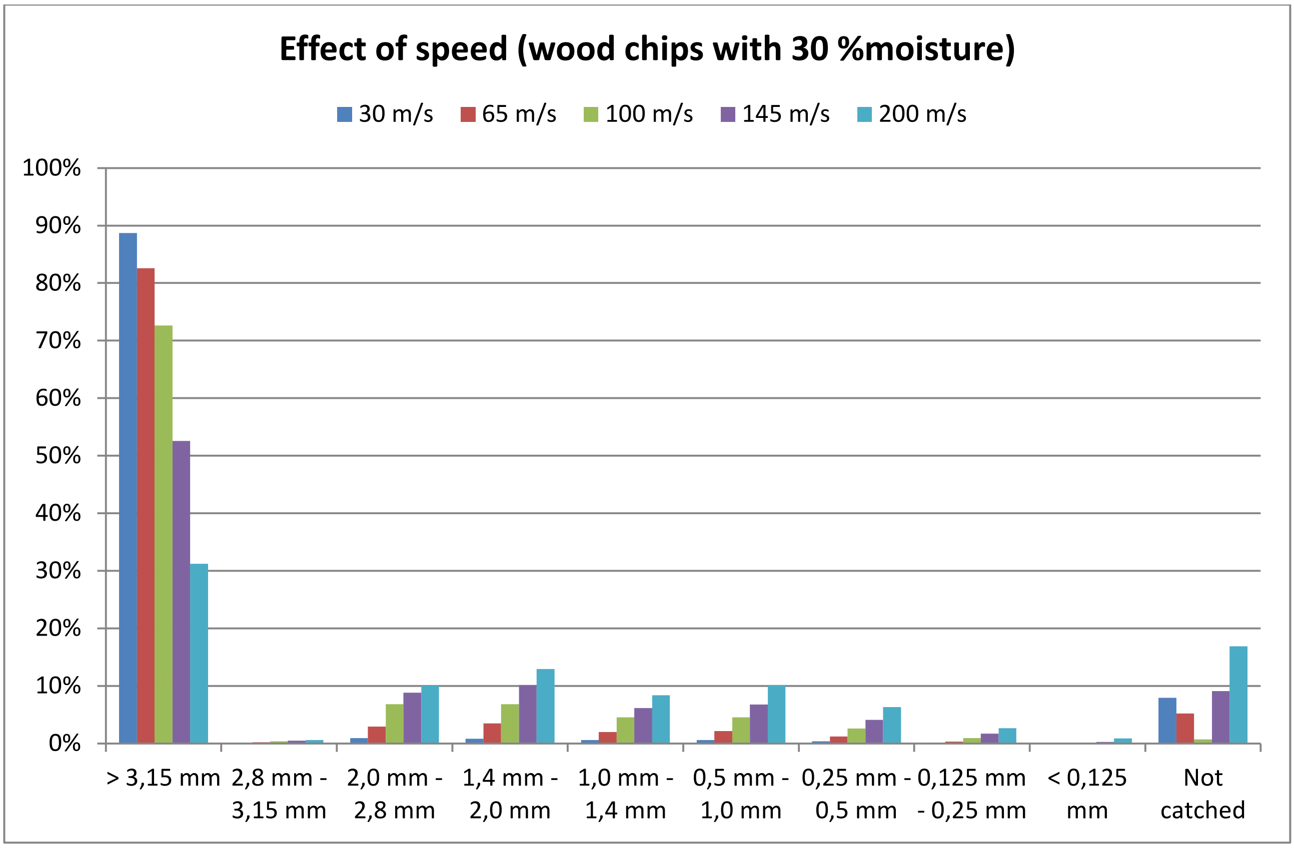


Chart 4. Particle distribution of downsized wood chips in function of the hammer velocity

This chart shows the particle distribution of the chopped material for a hammer speed of 30, 65, 100, 145 and 200 m/s, coming from 5 experiments with beech wood chips with a moisture content of about 30%.

Figure 11. Picture of chopped wood chips at different speeds.
From the left to the right: 30 m/s, 65 m/s, 100 m/s, 145 m/s and 200 m/s

It can be clearly seen on the graph and the pictures that the speed of the hammers has an important effect on the particle size distribution.
Tests at 30, 65 and 100 m/s do not show a high chopping effect.
With a hammer velocity of 145 m/s, all wood chips are broken into small pieces, but still ~50% of the particles are bigger than 3.15 mm.

Figure 12. Wood chips downsized at 200 m/s

The test at 200 m/s shows a significant decrease of the particle size. Only 30% of the particles are bigger than 3.15 mm. All particles bigger than 1.0 mm have a longitudinal shape. This shape has a lot of interest for combustion or gasification conversion.

The part of material lost during the experiment is significantly higher at 200 m/s. At this speed, the ratio of thin particles is higher. This observation is in agreement with the hypothesis that the “not caught” part corresponds to particles that are too thin to be caught by the collecting system.

6.4.4. Effect of moisture

Three experiments have been conducted to study the impact of the moisture content of the material on the chopping efficiency. All of these tests have used beech wood chips:

- 5% moisture: wood chips kept 48 hours at a temperature of 105°C. The moisture content decreased to 2.5% moisture but it increased back to around 5% before chopping (hygroscopic property of the wood)
- 30% moisture: the wood chips bought for this project came with a moisture content of 30%
- 60% moisture: wood chips with 30% moisture content have been immersed into water for 10 days. The resulting moisture content is about 60%

Hereunder is the graph of the particle size distribution for the 3 different moisture contents:

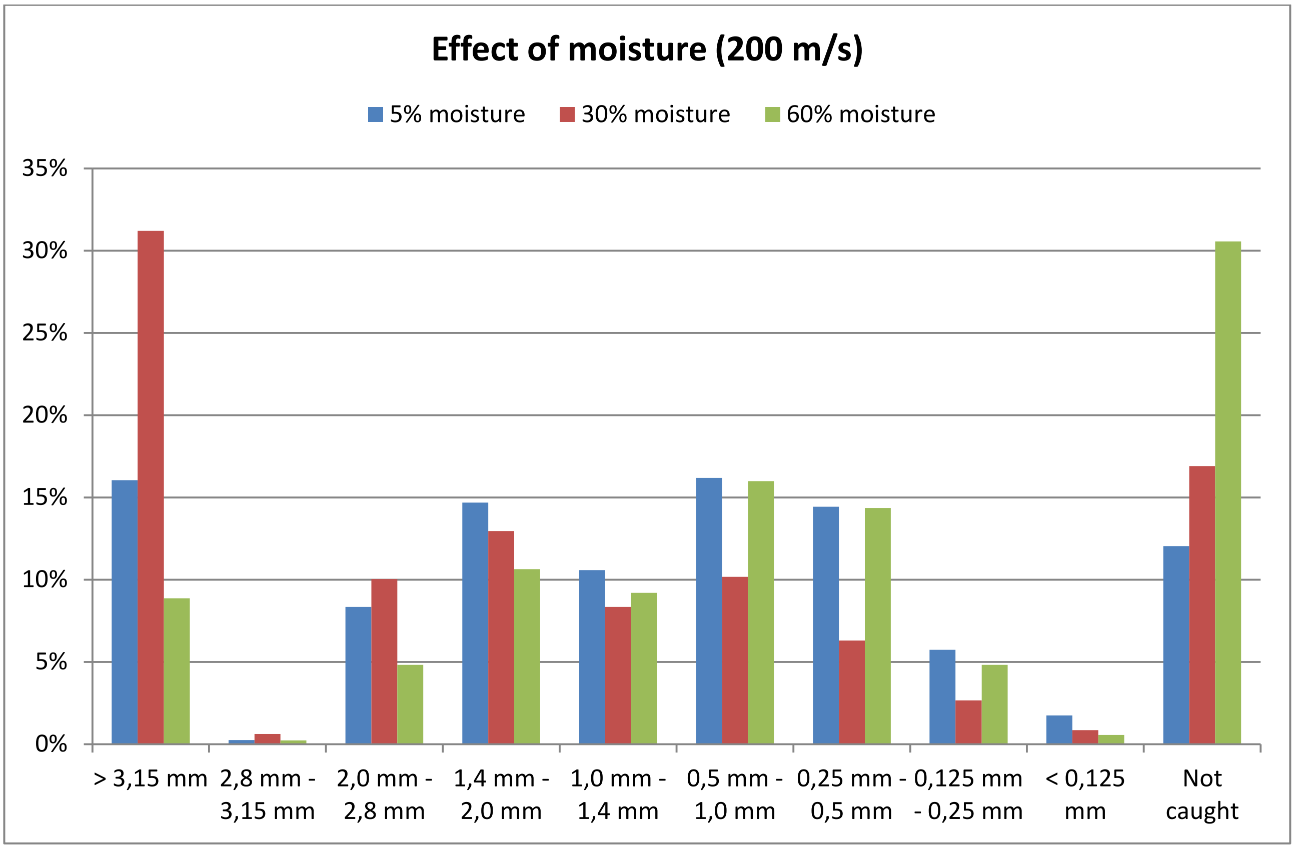


Chart 5. Particle distribution of downsized wood chips at different moisture contents

The first element that is necessary to point out regarding these results is the test with a moisture content of 60%. The part of material not caught during the experiment is quite high compared to the two other tests (>30%). The important variation comes from two reasons: the high moisture content made the particle sticking on the collecting system walls (funnel, pipe, and cylinder) resulting in a loss of some of the material; the second explanation is that the high air flow might have dried the material during the experiment resulting in another loss of mass.

The results of this test with 60% moisture must therefore be interpreted with precaution. It cannot be concluded that the chopping efficiency is higher when the material has higher moisture content.

The experiments at 5% and 30% moisture contents even tend to an opposite effect. Indeed, there are two times less particles bigger than 3.15 mm at 5% moisture content.

Concerning the shape of the particles, the pictures here below of the largest particles do not show a significant difference between the two different tests. In both tests particles are longitudinal, some of them are compact and some of them have their fibres open.

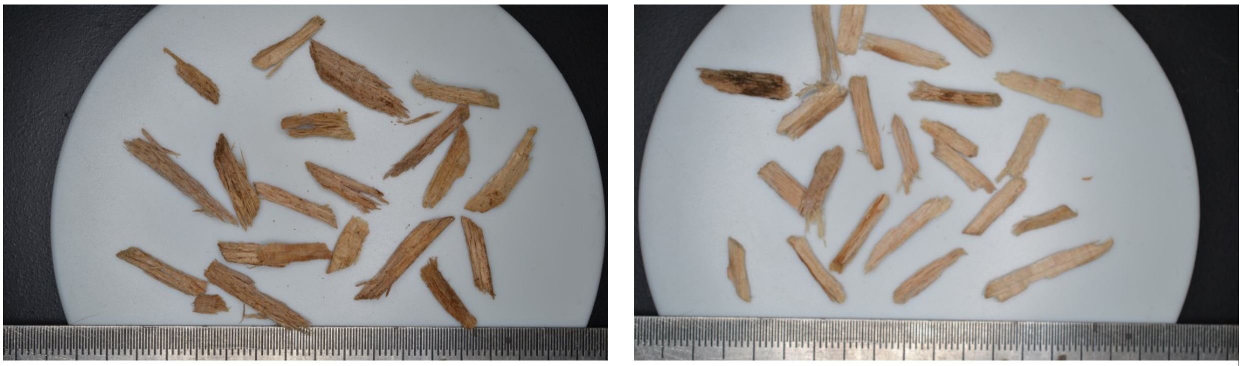


Figure 13. Comparison of large particles: Left=30%moisture, Right=5%moisture

The conclusion of this experiment series is that lower moisture content in the biomass increases the efficiency of downsizing. This element could influence the choice of placing the downsizing step before or after a potential drying step in a global process; of course the drying efficiency of downsized or non-downsized would have to be taken into account too.

6.4.5. Effect of temperature

Two experiments have been conducted in order to evaluate the impact of temperature on downsizing efficiency, and more specifically, the effect of heating the biomass at a temperature higher than its glass point. At 120°C has wood a glass point where its strength is significantly lower. Therefore, an experiment has been done with beech wood pellets heated at a temperature of 150°C, and compared hereunder with similar wood pellets at ambient temperature.

Both inlet materials have been previously dried and their moisture content is lower than 5%.

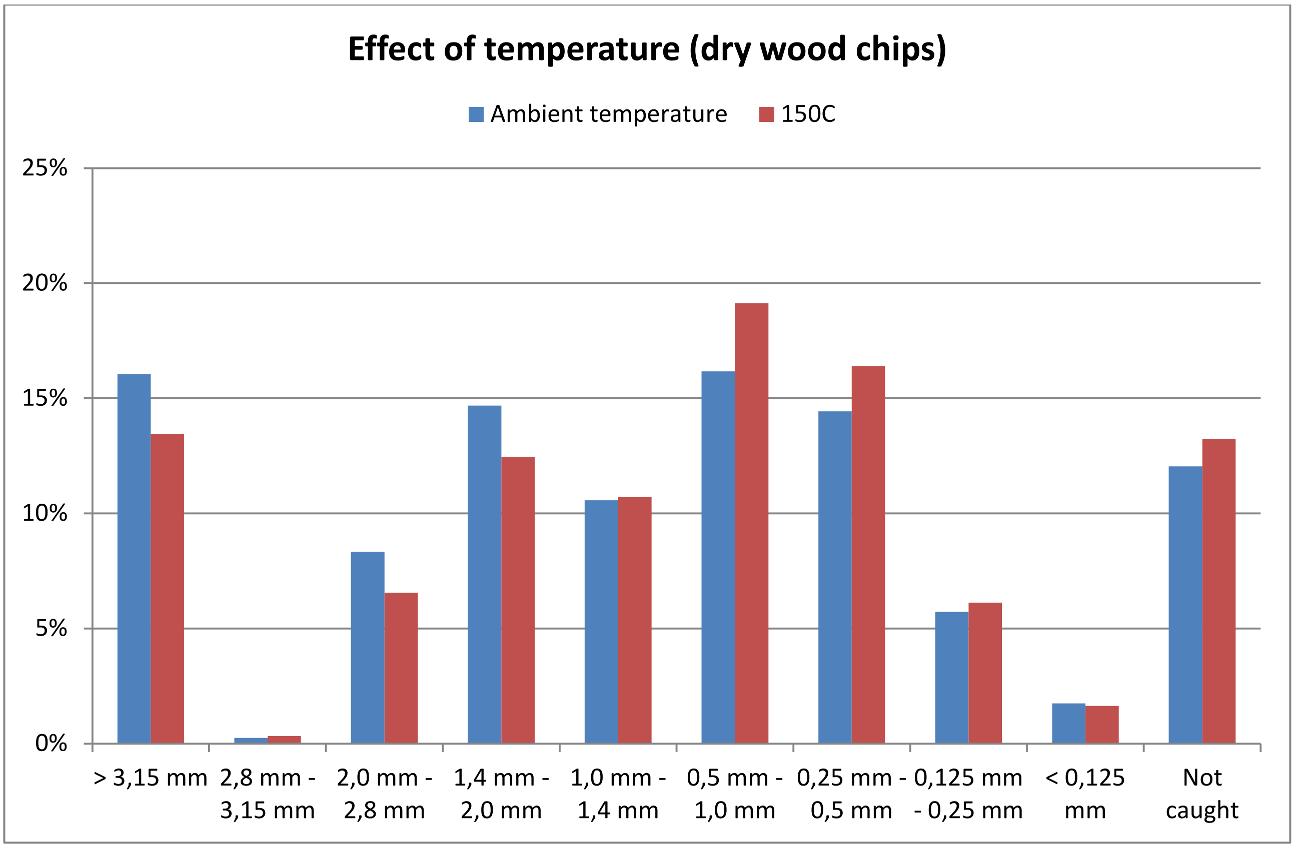


Chart 6. Particle distribution of downsized wood chips at different temperature

The comparison of both experiments at ambient temperature and at 150°C does not show a significant change in the resulting powder. The difference is within the experiment uncertainty and it is therefore not considered significant.

The information that can be taken from this chart is that temperature does not influence much the downsizing step. There is no point in heating the biomass before downsizing but in another side, if the biomass comes warm, from a drying step for instance, there is no need to cool it before chopping regarding the efficiency.

6.4.6. Effect of recirculating the material

6.4.6.1. Recirculation of all the material

A series of three experiments has been made focusing on recirculation of the material through the chipper. The first test downsized beech wood chips. This downsized material has been put back into the feeding bin and chopped again during a second test. The same procedure has been repeated in a last experiment being equivalent to three chopping cycles.

The chart below shows the particle size evolution in function of the passing number through the chipper:

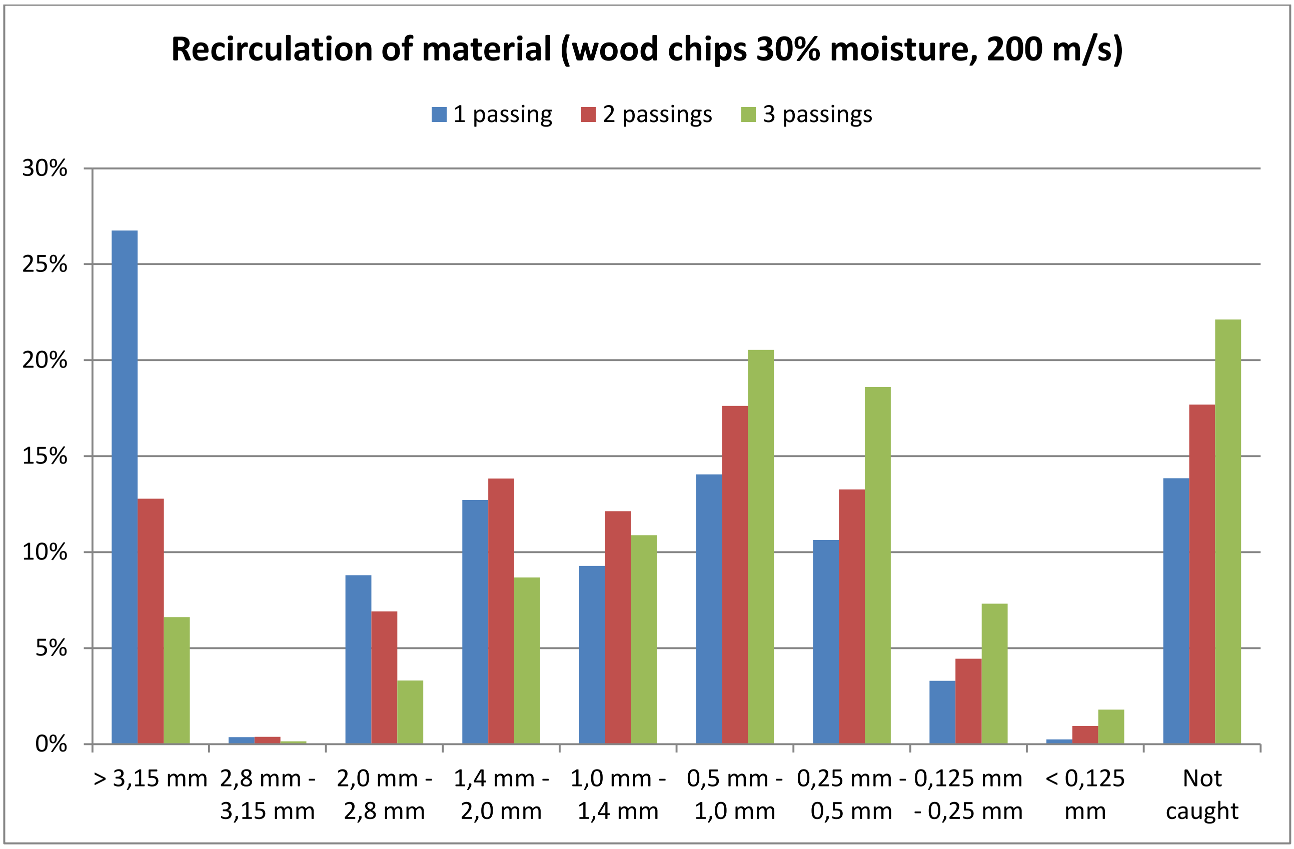


Chart 7. Particle distribution of wood chips chopped several times

There is a clear impact of recirculating the material into the chipper. The proportion of particles bigger than 1 mm decreases from ~60% to 45% and finally 30% after 3 chopping cycles. Besides that, the quantity of particles bigger than 3.15 mm is divided by 4 after two recirculations.

With these results, a shape analysis of the biggest particles is pertinent to couple with. It is presented hereinafter.

Figure 14. Picture of fraction > 3.15 mm after 1, 2 and 3 passages through the chipper

The pictures from Figure 13 show a change in the particles shape after each passing. After one passing through the chipper, most of the particles still have a compact shape. But after each extra chopping, particles become more frayed and the fibres more separated from each other.

The change in size can also be pointed out. In addition of decreasing the proportion of large particles, the pictures show that the larger particles are reduced in size. They do not exceed 3 mm in width after two re-circulations.

In summary, recirculating the material through the downsizer induces to:

- A significant decrease of the proportion of large particles: less than 30% of the particles are larger than 1 mm after two re-circulations
- A change of the particle shape: the particles become frayed resulting in a higher surface area

6.4.6.2. Re-circulation of the fraction > 1 mm

In order to compare the effect of recirculating the material, a series of experiments has been conducted with recirculation of the fraction > 1 mm only. Once the wood chips have been downsized by the mill, the material is sieved to separate the fraction > 1 mm and reintroduced it into the downsizer. This procedure is repeated a second time.

The results are presented below and a comparison with the first recirculation method is then discussed.

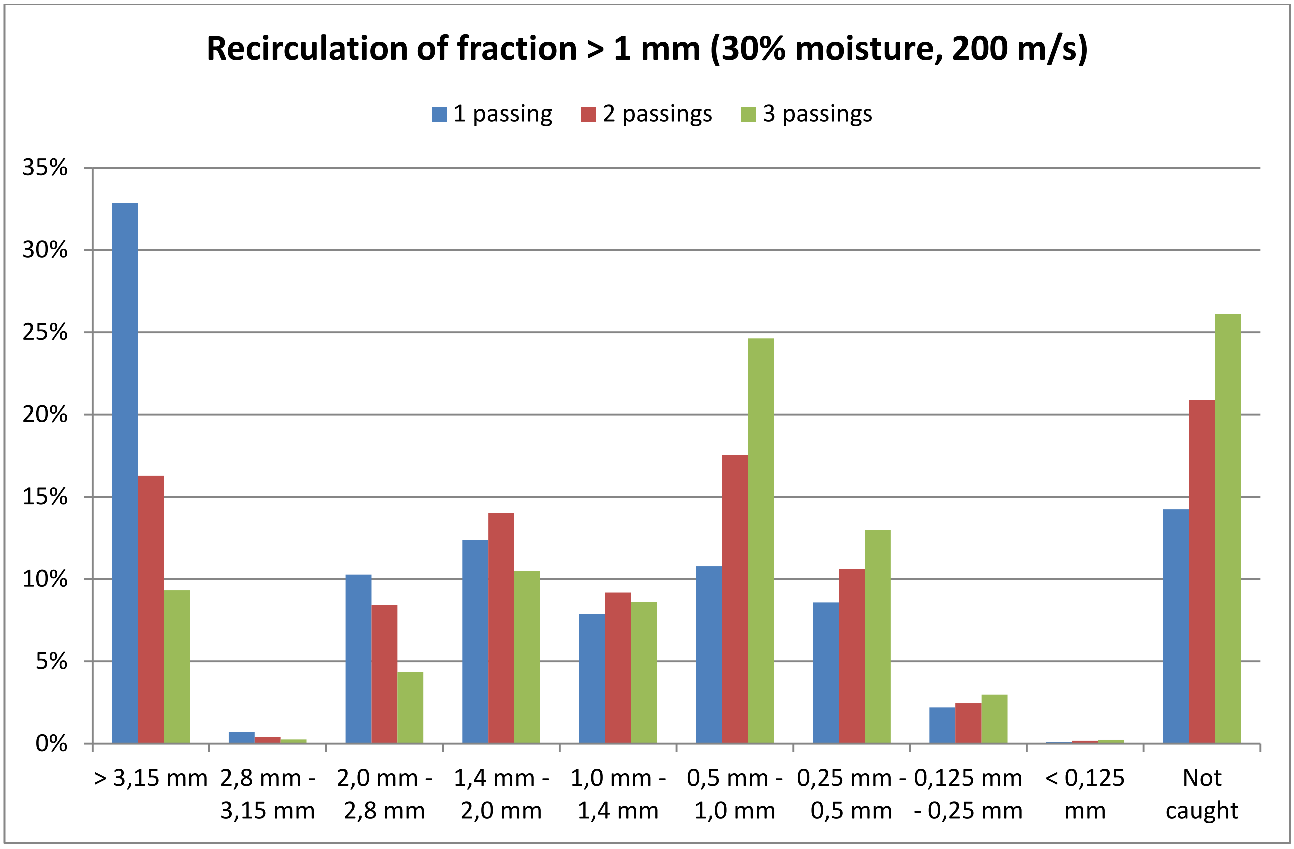


Chart 8. Particle distribution of downsized wood chips with re-circulation of the fraction > 1 mm

The difference between this experiment series and the previous has to be counterbalanced. Indeed, the particle size distribution of the material after one passing is slightly different in the two experiment series because of the variability of the experiment (e.g. +6% for the largest fraction).

However, this graph shows a similar tendency, with a decrease of the fraction > 3.15 mm by a factor of 3.5. The same change in the particle shape has been observed.

6.4.6.3. Comparison of the two methods

The difference in the proportion of particles > 1 mm from the two experimental series is illustrated by the chart hereunder.

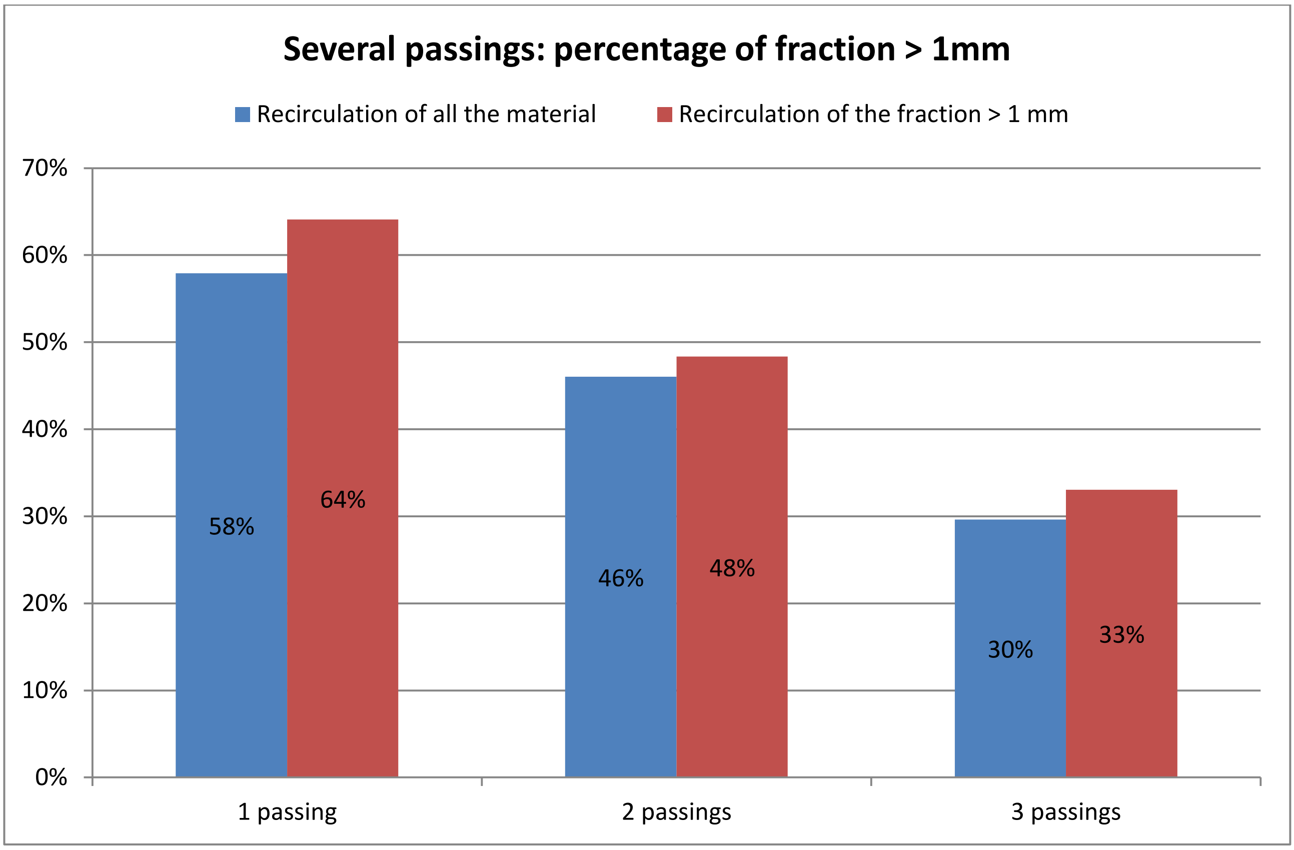


Chart 9. Comparison of the two recirculating methods

This chart reflects a similar evolution regarding the ratio of particles > 1 mm. The deviation is within the uncertainty of the experiment and is therefore delicate to comment.

The principle of the first method can be assimilated to a downsizer with several layers of hammers, wherein all the material would go through a first layer of milling, then through a second and a third one before to exit the mill.
The second method can be considered as an equivalent of a downsizer with only one layer but where the largest particles would be separated and re-introduced into the mill.

The two series of experiments do not result in a significant difference of the downsizing efficiency. If recirculating the material, the choice will be based on other parameters (e.g. energy efficiency).

6.4.7. Effect of speed on wood pellets

The experiments have ended by downsizing wood pellets at 5 different velocities (30, 65, 100, 145 and 200 m/s).

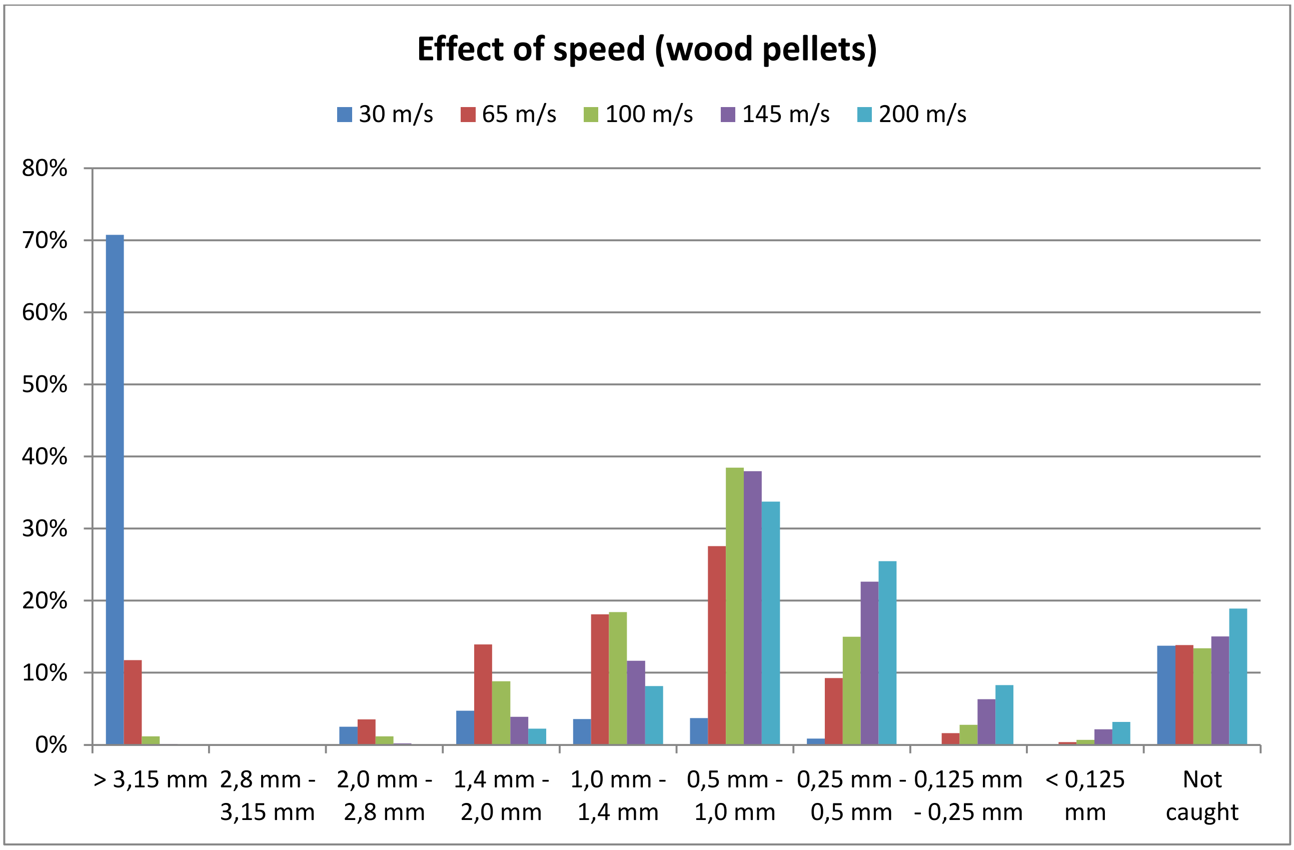


Chart 10. Particle distribution of downsized wood pellets in function of the hammer velocity

At 30 m/s, the mill has only a low effect on the wood pellets, only breaking them in few pieces. At 65 m/s, few particles remain bigger than 3 mm but the wood pellets are then downsized into a thin powder from a velocity 100 m/s.

These experiments show that wood pellets can be easily downsized to a thin powder by the mill and this with a low energy consumption (< 15 kW without basic hammer design).

Figure 15. Picture of downsized wood pellets at 100 m/s

6.4.8. Wear of the hammers

As explained in part *4.2.3. Hammers* the hammers are made of soft steel, making easy the observation of wear and damages. The following pictures show the state of the 4 hammers after approximately 40 downsizing cycles (= pre-tests, experiments and demonstrations).

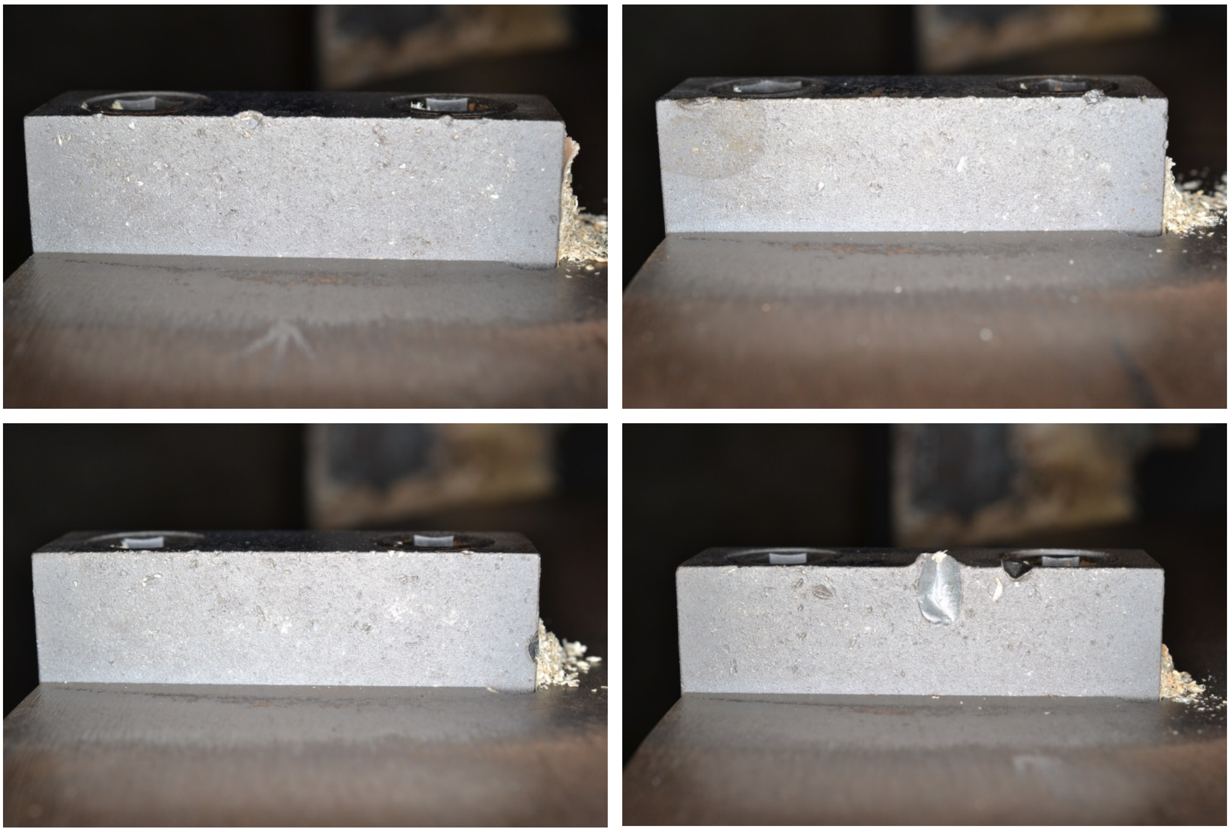


Figure 16. Pictures of the 4 hammers

Some wear can be observed on the surface of the 4 hammers. The amount of wear is however not considered critical and could be easily reduced by a surface treatment of the hammer and/or using a harder grade of steel.
The development of the NOWEAR downsizer must include the design of hammers resistant to wear.

Concerning the damages, it can be seen that one of the hammer (picture on the bottom right) has endured two important impact marks. It is assumed that these damages do not come from collision with wood material.
An explanation here could be that one or several foreign pieces have been injected into the mill with the biomass during the experiments. They could be a bolt or a small piece of steel introduced by inadvertence with the material into the downsizer.
A situation of this kind will be likely met in an industrial process where a high flow of material is chopped and can contain some foreign materials. The damages are nevertheless not critical for the operation of the mill and would be reduced by the use of harder hammers.

7. Perspectives

This project constitutes an interesting approach in order to dimension the NOWEAR downsizer. Thanks to the experimental tests, the parameters that impact or not the chopping efficiency are known.

Regarding the design of the NOWEAR downsizer, the main elements that will require some development are:

- The hammers
  - First, an engineering phase focusing on the shape of the hammer has to be conducted, with the aim of reducing significantly the power consumption by improving the aerodynamics of the hammers.
  - Secondly, a stage of selecting a harder material and potentially a surface treatment should be carried out in order to improve the resistance of the hammers to wear and damages.
- An efficient particle collecting system
  - The NOWEAR downsizer will be built in a closed system. This point will contribute to reducing the amount of material lost during the experiments. In addition, an efficient collecting system must be found in order to separate the wood particles from the air flow. A cyclone could be part of the solution.
- A particle classification system
  - The experiments have shown the benefit of chopping the biggest particles several times. Several layers of a disc and hammers is however not viable considering the energy consumption. One way would then be to separate the biggest particles from the outlet flow and reintroduce them into the inertia mill. It requires the development of a fast and reliable particle classification system. A gravity system could be developed to fulfil this function.
- The introduction of material to the mill
  - The pre-tests have shown a large influence of the downsizing efficiency depending on where the biomass was introduced. An introduction system has to be considered where as much of the material as possible is hit rather than blown through the system.

Concerning the elements that would be relevant to go into in depth:

- A study of the vibrations of the system
  - The vibrations produced by the downsizer must be studied in a next step of the development in order to get data. A measurement and acquisition system must be developed in order to understand and quantify the different vibrations phenomena generated by the mill.
- A determination of the surface area of the particles downsized
  - The surface area of the particles is considered as an important parameter for energy production processes and it will therefore be essential to look at it more specifically. Significant changes in the shape and porosity of the particles have been observed in this project and need to be quantified, by the BET method analysis for instance.

Based on the results from the experiments of this project, an estimation of the power consumption expected for a demonstration downsizer of 5 T/h wood chips is presented below.

It is estimated that the improvement of the introduction system will lead to reaching the target size of the particles after 2 re-circulations of the particles bigger than 1 mm.
The energy required to break the particles, equivalent to the kinetic energy of accelerating the particles to 200 m/s, is calculated hereunder:

biomass flow	5,0	T/h	
	1,4	kg/s	
speed of impact	200	m/s	
downsizing power consumption for 1 cycle	27,8	kW	[$\dot{m}.v^2/2$]
with 1 recirculation	55,6	KW	
with 2 recirculations	**83,3**	**kW**	

Experiments have shown that the power consumption to run the inertia with a hammer speed of 200 m/s is 120 kW. However, by improving the hammer design, operating in a closed system and reducing the pressure, it is expected reduce at least by a factor of 2 the power consumption of the inertia mill.

In this case, the total power consumption required to downsize 5 T/h of wood chips is expected to be:

power consumption 200 m/s	60,0	kW
chopping 5T/h with 2 recirculations	83,3	kW
Total power consumption	**143,3**	**kW**

Relating to the biomass flow, it is obtained:

Power consumption / ton biomass	28,7	kWh/T

In the evaluation presented in Appendix no. 1, a power consumption of 8.3 kWh/T is calculated for a single hit of the particles. Considering that we hit 3 times the particles (3 x 8,3 = 24,9 kWh/T) and the energy necessary for moving the hammers, the power consumption expected and based on this first project is very close to the initial model.

If the further improvements of the NOWEAR downsizer lead to reducing the power consumption to 28.7 kWh/T, then the downsizing step would represent only 0.6% (0.1 MJ/kg) of the wood heating value (18 MJ/kg).

8. **Conclusion**

This project, conducted by TK Energy and with the support of EUDP, has focused on experimentation of an innovative inertia mill for the downsizing of biomass. The purpose of this project was to obtain data for dimensioning the NOWEAR downsizer.

The project has been through the following phases: design, production and mounting of the prototype, pretesting and improving, and finally experimental testing.

The conclusions that can be made from this project are:

- The inertia mill can downsize wood chips and wood pellets to millimetric powder
    - Wood chips are efficiently downsized at a hammer velocity of 200 m/s
    - Wood pellets are efficiently downsized at a hammer velocity of 100 m/s
- The temperature of the biomass has no significant effect on the downsizing
- The moisture content of the biomass influences the downsizing efficiency: a lower moisture content results in a better downsizing
- Recirculating the biomass several times through the mill has a significant effect on the global particle distribution and on the shape of the biggest particles
    - 70% of the particles are smaller than 1 mm after 2 re-circulations
    - The biggest particles become open and frayed
- The introduction of material to the downsizer is critical in order to reach as high as possible fraction of the biomass that is hit by the hammers
- The amount of wear at the surface of the hammer is not considered critical and could easily be handled by using harder material or surface treatment
- The amplitude of vibration generated by the mill is surprisingly low and is favourable towards long lifetime

The parts that have been identified as key in the development towards an industrial product are the improvement of the hammers and the particle collecting system, the development of a particle classification system, and the measurement of vibration and particle surface area.

During the project, TK Energy has been approached by several potential customers and demonstrated the technology. In order to get closer to an industrial product, TK Energy will apply for support from EUDP for the development of a downsizing demonstration plant.

9. Appendix no. 1

Rough evaluation of energy for grinding

JM Seiler, November 2014

A Model 1

Basic idea:

Grinding means physically: Deformation of the material up to rupture. Several deformations of the same material may be necessary to come to a small size (200 µm).

Energy of deformation to rupture is given by:

$$E = Vol\int_{0}^{\varepsilon d} \sigma \, d\varepsilon \qquad \text{Rel(1)}$$

with:

Vol: volume of the particle (m3)

ε : strain

ε_d : rupture strain

σ : stress (Pa)

In the following , Rel (1) will be simplified to:

$$E = Vol\, \varepsilon_d \sigma_y \qquad \text{Rel (2)}$$

with:

σ_y : yield stress (Pa)

Number of particles and number of ruptures:

The final number of particles is:

$$N = \frac{Vol}{\frac{4}{3}\pi R^3}$$ where R is the radius of the final particles (say ~100 µm)

Number of deformations of the whole volume:

If we suppose now that the particles are produced in the following way:

1) the chip is deformed and cut into two pieces
2) the two pieces are deformed again and cut into two pieces each (i.e.: 4 pieces after second cut)
3) the four pieces are deformed and cut into two pieces each (i.e. 8 pieces after third cut)
4) etc…

… we can relate the number of deformations (n), of the whole volume, and successive cuts that are necessary to obtain the final number of particles (N) by:

$$N = 2^n \qquad \text{Rel (3)}$$

Thus:

$$n = \frac{LnN}{Ln2}$$

Energy:

The total energy that is necessary is then given by:

$$E = Vol\,\varepsilon_d \sigma_y \frac{LnN}{Ln2} \qquad \text{Rel (4)}$$

with $N = \frac{Vol}{\frac{4}{3}\pi R^3}$

For a mass M tonne of dry wood (intrinsic density: ρ):

$$E = \frac{M}{\rho}\varepsilon_d \sigma_y \frac{LnN}{Ln2}$$

$$N = \frac{\frac{M}{\rho}}{\frac{4}{3}\pi R^3} \qquad \text{Relations (5)}$$

Normally, we should subtract the energy that is (not) required to get the initial chips of characteristic radius R0:

$$E = \frac{M}{\rho}\varepsilon_d\sigma_y(\frac{LnN}{Ln2} - \frac{\ln N_0}{Ln2})$$

with

$$N_0 = \frac{Vol}{\frac{4}{3}\pi R_0^3}$$

After some calculations, we obtain:

$$E = \frac{M}{\rho}\varepsilon_d\sigma_y(\frac{LnN}{Ln2} - \frac{\ln N_0}{Ln2}) = 4{,}33\frac{M}{\rho}\varepsilon_d\sigma_y Ln\frac{R_0}{R} \qquad \text{Relation (6)}$$

Application:

M=1tonne

ρ = 500 kg/m3

ε_d : rupture strain ~0,3

σ : stress (Pa)

σ_y : yield stress (Pa) ~50 MPa

R= 100 µm

R0=0,03 m (wood chips)

We obtain:

E= 7,41 10^8 Joules/t = **206 kWh/t**

The order of magnitude is not ridiculous!

Minimum energy

According to this approach, the minimum energy is obtained when all particles are produced from a single deformation and is equal to:

$E = Vol\,\varepsilon_d \sigma_y$ Rel (2)

which is ~30 MJ/t or **8,3 kWh/t**

There is a huge difference between this minimum energy and the energy generally required for grinding (several 100 kWh/t). The difference comes from the fact that the same material has to be deformed several times until the small size is reached.

10. Table of figures

11. Table of charts