Versatile Grinder Technology for the Production of Wood Biofuels

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Abstract

The exploitation of wood biomass for thermal energy production often represents an effective complementary source to petroleum, especially where there is the availability of extended forests. Focusing the attention on household plants, the wood pellet currently constitutes a widespread biofuel, which however is characterized by non-negligible production costs. Wood microchips constitute a recently developed alternative, which compensates its inferior characteristics by an easier production process. To obtain these biofuels, the particle size reduction is crucial, because it sensibly influences the power consumption of the drying processes, as well as the raw material supply strategies. In this context, this paper presents an innovative grinding technology, which can be exploited to produce wood particle sizes for both wood pellets and microchips production. In particular, the prototype of the grinder and the experimental plant are shown, which have been used for performing preliminary biofuel production tests. The main design characteristics of the prototype are provided, together with preliminary experimental results that provides first evidences about the potentialities of the proposed wood grinding technology.

Keywords: wood pellet; microchips; grinding; wood grinder; biofuel; wood drying.

1 Introduction

The woody solid biofuels represent a relevant energy source for heating and power generation. This is especially true for those territories characterized by the presence of vast wooded areas. Accordingly, Europe acknowledges high consumptions of wood pellets for thermal energy production in household plants (more than 18 million tonnes in 2014) [1], which is expected to further increase by 2020 [2]. The wood chips production follows the same trend of the pellet but the research of new biofuels is still an on-going activity that can provide hints for new fuel alternatives. For example, an additional bio-fuel type is currently under investigation, i.e. the “wood microchips”. Notwithstanding the lower energetic content (which can also be affected by the storage conditions [3]), this new biofuel is a real alternative to wood pellets, thanks to the limited moisture content of microchips (between 10% and 15%) and the specific particle size. Indeed, with minimal modifications to both feeding mechanisms and combustion controls, microchips can be used to feed conventional pellet stoves and boilers. Moreover, it can be easily manufactured by small enterprises using locally available raw materials and with low-investments [1].

The pellet production process starts with a primary grinding (chipping) of wood biomass to obtain chips having a variable size [4–6], whose moisture content is drastically reduced to 20% in weight by means of drying ovens. Then, a further grinding phase is required, to obtain finer particles, whose moisture content is further adjusted to 10-12% in weight. Then, pellets are obtained through a pressing and extrusion process. Differently, since wood chips with a length between 5 and 10 mm compose wood microchips, they can be obtained by particular settings of common wood chippers (i.e. reducing the clearances between chippers’ blades and related discs or drums, and reducing the feeding speed). However, the standard ISO 17225-4 prescribes that a mass unit of high-quality microchips should be composed by a 60% in mass of particles between 3.15 mm and 16 mm, no particles bigger than 31 mm, while smaller particles should be reduced under the 1% in mass. Therefore, a sieving process is required to obtain the desired quality.

It is not in the scope of the paper to discuss about pros and cons of the two biofuels, while it is worth to highlight the following issues.

Considering wood pellets, the required dewatering processes involve a non-negligible amount of thermal energy [7], e.g. for belt dryers it has been estimated that the thermal energy spent for drying wood chips is about the 25% of the whole pellet production process [8]. Although different types of drying oven can be used [9,10], also powered with renewable energy [11] or with a part of the wood biomass, this particular step is critical especially for small production plants [12]. It is acknowledged that the particle size heavily influences the process time in heating-based dewatering systems (the higher the particle size, the higher the time required for drying) [13,14]. However, smaller wood particles could lead to negative effects for certain drying models (e.g. the deep bed one [15]). Nevertheless, smaller particles also allow to exploit lower drying temperatures, and particular dryers have been developed accordingly [8], which can lead to lower the drying energy consumptions. Unfortunately, current mills available for refining wood chips into sawdust, encounter severe problems when they process wet biomass (i.e. green wood). One of the most diffused types of refining technology for woody biomass is that of hammer mill [8,16–18], which uses a static selective grid to obtain the desired particle size [19,20]. However, the wet sawdust produces a sort of extremely viscous pulp that rapidly obstructs the grid openings, leading the mill to jam [8]. Therefore, it is necessary to reduce the moisture content of wood chips to allow the use of the hammer mill, thus hindering the exploitation of the potential advantages coming from drying smaller particles.

Additionally, it has been observed in literature that powerful ultrasonic waves can further contribute to moisture reduction [21]. Accordingly, some devices can be found which claim to adopt high-speed mechanical energy for both comminution and dewatering of particles [22–24]. However, after more than 20 years from the first patent, this technology still not spread in small-scale pellet plants, as in Italian forestry sites. One possible reason could be that sizes, dimensions, complexity and design mass flow rates justify the costs of this system only for production plants characterized by high productivity (several tonnes per hour).

Concerning microchips production, the setting of wood chippers to obtain the required particle sizes involves the reduction of the productivity while the percentage of smaller undesired particles sensibly increases. Moreover, the sieving process introduces an upper limit to the yield of microchips, i.e. the obtained quantity will be always a fraction of the total processed wood. A possible alternative is producing coarse wood chips with a chipper, set at its maximum productivity, and then to refine the produced chips with a refiner capable to transform almost the total mass of processed wood into the desired microchips. This would allow a continuous process with maximized output yield and production rates but it is unclear whether current refiners can produce the required particle size distribution without increasing the percentages of smaller particles.

In such a context, the paper presents a new grinding technology capable to process green wood chips to produce sawdust for pellet production, and microchips. In light of the state of the art shortly introduced in this section, the main requirements of the new grinding technology are:

- Throughput compatible with small pellet production plants (up to 1 tonne/h);

- Produce sawdust from wet woodchips to allow the reduction of drying energy consumptions.
- Produce microchips from wet wood chips, with reduced production of undesired smaller particles.
- Perform preliminary investigations about the adoption of “high-speed” mechanical energy to remove part of the moisture content.

Preliminary tests for the production of pellets and microchips have been performed with a proof of concept prototype [25] of the grinder, installed in an specific experimental plant.

2 Materials and methods

2.1 *Prototyping the grinder*

The prototype is a multi-stage rotational and centrifugal grinder, where the raw material is introduced axially and then propelled across static and rotational cutting stages. The main parts constituting the prototype are shown in Figure 1, and details about both the rotor and the stator assemblies are depicted respectively in Figure 2 and Figure 3.

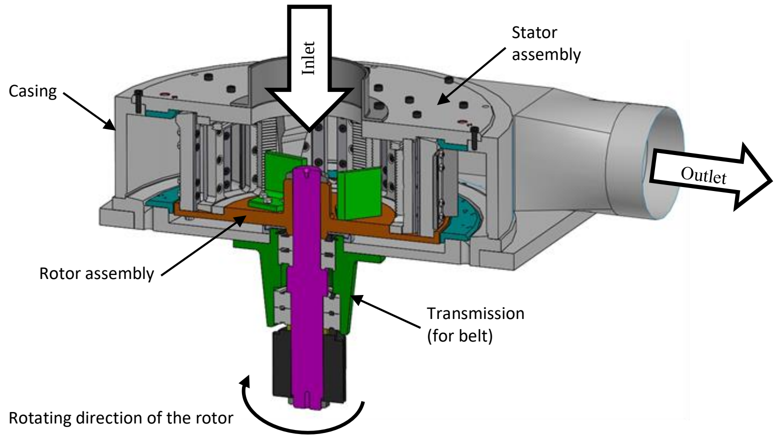

Figure 1. Main parts of the centrifugal grinder prototype. Lateral section view.

As shown in Figure 2, a basement constitutes the rotor, which holds a set of internal propelling blades and two cutting stages. A number of vertical columns characterize the first stage, where a threading is present on both the inner and the outer surfaces. This particular profile constitutes the cutting edges for the first comminution stage. The second stage is constituted by a higher number of columns, where both cutting and external propelling blades have been secured by means of screws and bolts. The basement is linked to the transmission shaft by means of two keyways (see Figure 1).

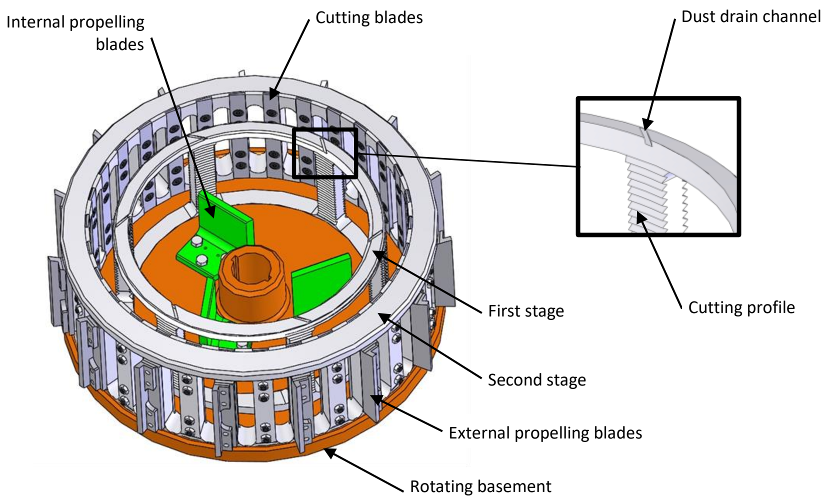

Figure 2. Rotor assembly (to provide a dimensional reference: the external diameter of the rotating basement is 288 mm).

Each component of the rotor assembly has been designed to reach a maximum rotational speed of 7500 rpm. In particular, each stage has been designed by considering the effect of an unbalancing mass of 100 g, acting on the middle point of a single column. The prototype has been built using a AISI1040 steel (or C40 steel according to the standard ISO 683-1). A lid holding two stator stages composes the stator assembly (see Figure 3). In particular, a ring with two or four teeth constitutes the first stator stage while a ring with a number of openings constitutes the second stator stage. The cutting profiles of both stages have been obtained through threading.

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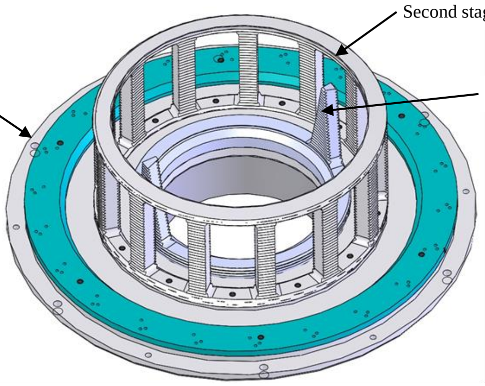

Figure 3. Stator assembly (to provide a dimensional reference: the external diameter of the lid is 380 mm).

Once assembled to the casing (see Figure 1), stator and rotor assemblies form a particular “comminution chamber” (Figure 4), were the conjoint action of centrifugal forces, airflow and the sequence of rotor and stator stages, allows the comminution of the wood particles introduced in the chamber as shown in Figure 1.

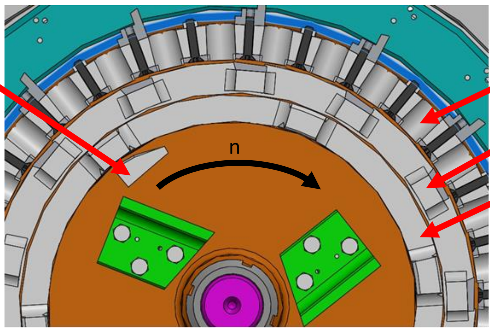

Figure 4. Internal view of the comminution chamber, where "n" indicates the rotational speed (rounds per minute) of the rotor assembly.

Indeed, the internal propelling blades (see Figure 2) provide a tangential motion to wood particles and, consequently, a radial acceleration due to centrifugal forces. Similarly, also each rotor stage gives additional motion to particles. The radial acceleration compels particles towards the stator stages, and then, due to the motion of rotor stages and the thin gap (1 mm) between rotating elements and static elements, the particles are cut.

The internal propelling blades and the first stator stage perform a first rough cut of the bigger particles, while the other particles undergo the comminution performed by the first stator stage and the first rotor stage. Similarly, further comminution of smaller particles is performed by the first rotor stage and the second stator stage, and then by the second stator stage and the second rotor stage. Therefore, the external propelling blades and the airflow (mainly produced by the internal propelling blades) push the resulting particles toward the outlet opening (see Figure 1). The airflow is fundamental for the functioning of the system because it supports the passage of wood particles across the stages of the comminution chamber. However, although the rotating speed of the rotor assembly is proportional to the airflow rate, the higher the rotating speed, the smaller the produced wood particles.

Moreover, the airflow interacts with the alternation of static and rotating elements composing the comminution chamber, producing pressure waves. In other words, a “sentry-siren effect” is generated, with sound waves in the audible spectrum of about 100 dB measured at 1 meter of distance. Despite the high sound pressure level represents a potential limitation of this design, it actually constitutes an intrinsic functionality of the system, as discussed in the following sections. Both sound pressure and frequency clearly depend on the rotating velocity of the rotor assembly, because both opening-closing frequency and airflow rate depend on the rotating speed of this part. However, as for the experimental plant described in Section 4, it is possible to build a noise absorbing case around the machine to reduce the sound pressure level emitted into the environment.

2.2 *Testing and optimization of the prototype*

2.2.1 *The experimental plant*

The physical embodiment of the prototype has been mounted on an aluminium frame, together with a 30 kW AC motor and the related transmission belt (Figure 5). To test different rotational speeds, the motor is powered by an inverter, capable to set different current frequencies from 0 to 60 Hz. The number of electrical poles of the motor (two) and the speed ratio provided by the transmission belt, allow a maximum rotational speed of 6000 rpm at 50 Hz. With this specific structural embodiment, the maximum allowable throughput of the grinder is about 700 kg/h (considering moist wood chips from a mixture of chestnut, acacia and beech).

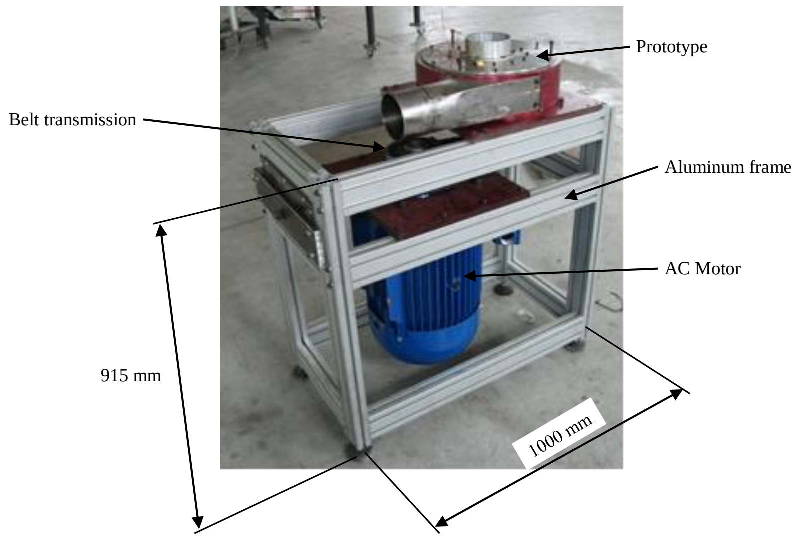

Figure 5. Embodiment of the prototype.

In order to identify the best grinder configuration for producing the desired particles, the prototype was designed by considering the possibility to test different configurations. Accordingly, two variants of both rotors stages and second stator stage (Figure 2 and

Figure 3) have been designed and manufactured, with different numbers of cutting blades (see Table 1).

Table 1. Rotor and stator stages variants.

	First rotor stage	Second rotor stage	First stator stage	Second stator stage
Number of blades variant n° 1	6	15	2	13
Number of blades variant n° 2	12	30	4	26

To perform comprehensive testing, also an experimental plant has been designed, whose main elements are depicted in Figure 6. In particular, a hopper with a feeding screw is used to contain the coarse woodchips and to control the mass flow rate. Then, an elevator (conveyor belt) brings the raw material to the inlet of the grinder's comminution chamber. In the same inlet, an additional tube is connected to provide the needed airflow (also a silencer is connected to the same tube). An outlet piping allows the output material to reach the separating cyclone where the airflow is divided from the obtained particles, which are collected on the ground.

Moreover, as shown in Figure 7, several sensors have been considered for the experimental plant, to perform a series of measures (mass flow rate, airflow rate, fluid-dynamic prevalence) and to monitor critical elements (bearing temperature and outlet airflow temperature). More specifically, to calculate the fraction of the fluid dynamic power of the total power consumed by the grinder (i.e. to isolate the actual grinding power), it is necessary to measure both airflow speed and prevalence. To this purpose, the passage of the air through the input wood chips is avoided by using an airtight lid to cover to the hopper, and by using an airtight cover for the elevator. In this way, input air can pass only through the related inlet tube, and a valve is used to regulate the airflow rate. These measurements are useful for understanding the behaviour of the prototype

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and testing different configurations between airflow rate, mass flow rate of wood and rotating speed.

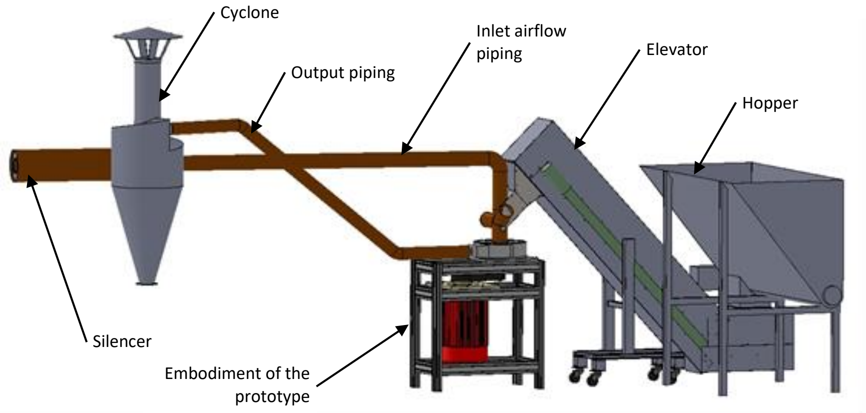

Figure 6. Main elements of the experimental plant.

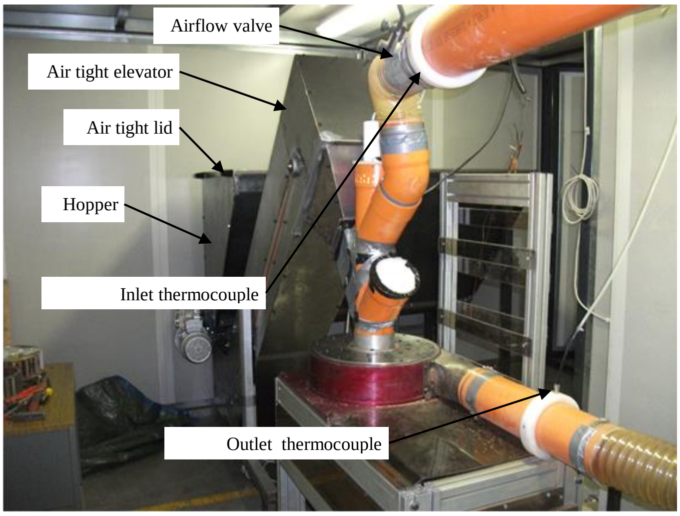

Figure 7. Internal view of the soundproof room. Frontal view of the main elements (the cyclone is located out of the room).

Additionally, a magnetic iron removal system was specifically built to eliminate possible iron splinters from chippers' blades and/or nails, bolts etc, which sometimes fall into the wood chips. More specifically, the system was composed by a series of sloped surfaces with opposite angles, disposed one upon the other, where high-intensity magnets were located. Then, wood chips were passed through these surfaces by means of gravity and vibrations.

2.2.2 *Instruments and monitoring system*

As introduced in the previous subsection, measurements and monitoring devices were used to assess the performance of the experimental prototype under different working conditions and to remotely monitor the correct functioning of the system.

The power consumption was measured by an electrical power analyser (CVM/Mini [26]). Among the different available data, it allows extracting the actual power consumption of the grinder in kW. The mean power values can be obtained by arithmetical average of a predefined number of instantaneous power values (e.g. six). The mass flow rate was controlled by regulating the rotational speed of the feeding screw internal to the hopper. To this purpose, a specific inverter was used to control the current frequency of the screw's electrical motor. Preliminary tests were performed to calibrate the feeding screw and to obtain the correlation between rotational speed and wood mass flow. Different curves have been obtained for different moisture contents of the processed wood chips.

To measure the moisture content of the wood chips, a commercial tool has been used, which allows to rapidly perform the measure with different particle sizes and wood types [27]. It allows to rapidly extract the percentage of the moisture content "M", according to the commercial standards (Equation 1):

$$M = \frac{P_u - P_0}{P_u} \times 100 \qquad (1)$$

Where P_u is the weight of the wet wood, and P_0 is the weight of the dry wood.

To characterize the particle size distribution contained in both the raw and the processed material, a manual sieve has been used, with three different grids. In particular, the first grid had a square mesh of 10 mm, the second grid a square mesh of 5 mm, and the final grid a square mesh of 2,5 mm. The sieve was capable to process samples of about one kg. Moreover, a scale with a resolution of 0.0001 kg was used to assess the weights of samples. In particular, the particle size distribution for each configuration was assessed (when needed) by sieving three samples of 1kg. Then, the weight of the material collected in each screen stage was measured and rounded to two decimal places (in kg).

To perform fluid dynamic measures, a Pitot probe (positioned in the air inlet tube) has been used, together with an electronic transducer and a multipurpose data acquisition board (with 0-10 Volts inputs). In particular, to measure the airflow rate within the inlet tube, specific activities were performed to establish the mean speeds. More precisely, after positioning the Pitot probe in the centre of the tube, the max speed can be obtained with Equation 2:

$$V_{max} = \sqrt{\frac{2\Delta p}{\rho}} \qquad (2)$$

where Δp is the pressure difference between the static and the dynamic pressures from the Pitot probe, and ρ is the air density. Then, the speed profile under the laminar flow hypothesis can be obtained [28], and the average speed can be calculated to estimate the airflow rate.

Thermocouples (K-type) have been used for monitoring bearing temperatures and to acquire air temperatures. Even in this case, a specific data acquisition board was adopted. A software tool specifically developed with LabView Signal Express® was used to control data acquisition.

Since the prototype has been enclosed in a soundproof room, it was necessary to remotely monitor its working conditions to rapidly and safely intervene when needed. To this purpose, a video monitoring system has been installed with four cameras, as shown in Figure 8. More specifically, the monitored elements were the inlet of the grinder (Figure 8a), the level of the hopper (Figure 8b), the elevator (Figure 8c) and the output of the cyclone (Figure 8d).

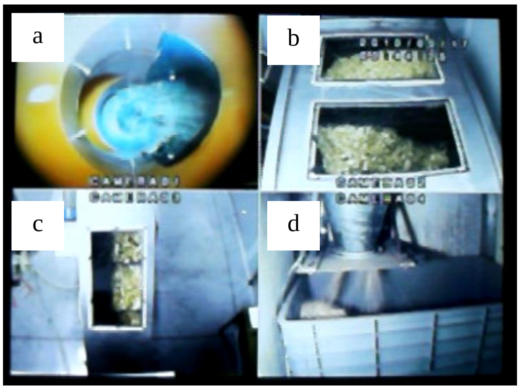

Figure 8. Video monitoring system: grinder inlet (a); hopper level (b); elevator (c), cyclone output (d).

2.2.3 *Raw material*

For tests related to sawdust production, coarse wood chips (mainly from chestnut, beech and acacia trees) were processed with the grinder prototype. The moisture content of the wood chips was about 45% (according to Equation 1), while the particle size composition was extremely irregular (as shown in Table 2 and Figure 9(a)), with some pieces larger than 100 mm.

Table 2. Particle size distribution of the raw material used for the sawdust production experiments.

	Sample 1	Sample 2	Sample 3	Mean %	St. dev.
Total weight (kg)	1.05	0.99	0.89	-	-
Weight (in kg) of particles >10 x 10	0.25	0.28	0.19	24,5%	3,5%
Weight (in kg) of particles >5 x 5	0.51	0.46	0.44	48,2%	1,5%
Weight (in kg) of particles >2,5 x 2,5	0.15	0.16	0.16	16,1%	1,8%
Weight (in kg) of particles < 2,5x2,5	0.14	0.09	0.10	11,2%	2,1%

For tests related to microchips production, the moisture content of the wood chips was almost the same (about 45%), while the particle size composition was quite different. The related percentages are shown in Table 3.

Table 3. Particle size distribution of the raw material used for the microchips production experiments.

	Sample 1	Sample 2	Sample 3	Mean %	St. dev.
Total weight (kg)	1.10	1.05	1.10	-	-
Weight (in kg) of particles >10 x 10	0.74	0.65	0.46	57,0%	13,4%
Weight (in kg) of particles >5 x 5	0.28	0.30	0.42	30,7%	6,6%
Weight (in kg) of particles >2,5 x 2,5	0.05	0.07	0.13	7,7%	3,7%
Weight (in kg) of particles < 2,5x2,5	0.03	0.03	0.09	4,6%	3,1%

3 Results

Several tests runs have been performed, spanned over different periods according to specific designs of experiments [29], mainly aimed at identifying both potentialities and structural issues of earlier prototype versions. More than 5 tonnes of coarse wood chips have been processed in these tests, and the following subsections show the results obtained from the experimental campaigns.

3.1 *Sawdust for wood pellet production*

Few clogging problems were encountered only when testing lower rotational speeds (under 3000 rpm) and lower airflow rates (closed air valve). In these cases, the produced sawdust was not capable to reach the cyclone and gradually obstructed the outlet duct. The consequence was a sudden stop of the grinder, which however did not cause any mechanical or structural problem.

A specific configuration was identified, which allowed producing the desired particle size (see Figure 9(b)) from wet chips without functional problems for the experimental plant. More specifically, a specific structural configuration of the grinder (from those available in Table 1) combined with a rotational speed of 6500 rpm, performed the best. Table 2 reports the actual grinder configuration.

(a) (b) (c)

Figure 9. Material transformation: input coarse wood chips (a); sawdust obtained with the prototype (b); pellet obtained from the produced sawdust (after the drying process).

Table 4. Rotor and stator stages for the preferred "sawdust" configuration of the grinder.

	First rotor stage	Second rotor stage	First stator stage	Second stator stage
Number of blades	6	15	2	26

Three mass flow rates were tested: 300 kg/h, 500kg/h and 700 kg/h. Visual evaluations revealed no evident differences among the particle sizes produced with the different mass flows. Additional analyses performed by an external laboratory reported that about the 85% in mass was between 3mm and 500μm, and only 4.5% was under the 200 μm. The same laboratory performed a pellet production test, where a sample of 50 kg of the produced sawdust was previously dried (to 10% of final moisture content) in a small rotary oven. The pellet was successfully obtained through a commercial mill, as shown in Figure 9(c).

Concerning power consumption, the mean power has been extracted from the specific measurement tool introduced in Subsection 2.2.2, with trials lasting about three minutes. After a first transitory regime (about 1 minute), power data has been manually collected (six values) in the remaining time for extracting the mean value. The obtained results are shown in Figure 10, were also the power consumption for 1 tonne/h has been estimated (26 kW) through a linear interpolation. However, the current prototype cannot reach such a mass flow rate.

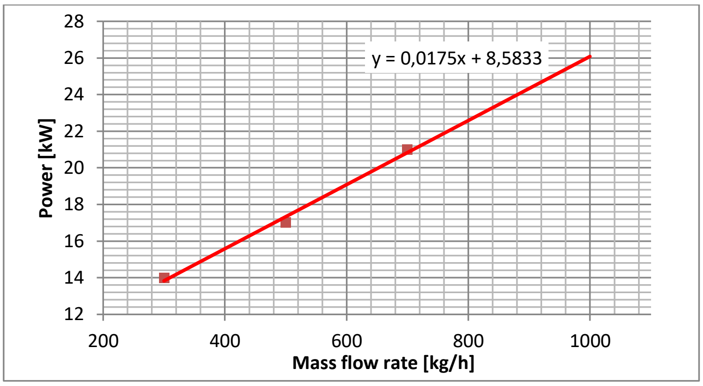

Figure 10. Power consumption for producing the sawdust shown in Figure 9~~Figure 10~~(b), at 6500 rpm and with different mass flow rates. Moisture content of the processed wood chips about 45% (Equation 1).

Considering that wood chips were characterized by a moisture content of about 45% (see Equation 1), the specific power consumption is 47 kWh per tonne of dry wood. The airflow rate, measured during material processing was about 700 m^3/h. Only a minimal reduction of the airflow is observed when the wood chips flow rate increases. Additionally, the concurrent dehumidification rate of about 5% (according to Equation 1) was observed for rotational speeds higher than 6000 rpm.

3.2 *Wood microchips production*

The tests performed in this case were sensibly influenced by non-negligible limits of the specific prototype, which was not originally thought for producing this kind of particles. To identify the most promising configurations of the prototype, a screening of the tests was performed to discard unfeasible configurations. Accordingly, it was found that for microchips production, the maximum rotational speed was 4500 rpm to limit smaller particles, while the lowest admissible speed was 3500 rpm under which the prototype rapidly encounter clogging problems. Moreover, it was not possible to use the separating cyclone, since the reduced airflow was not sufficient to push the bigger particles along the outlet piping. Therefore, the processed material was projected directly on the ground, just near to the prototype.

A specific configuration was identified, which allowed producing microchips with limited production of finer particles (see Table 5).

Table 5. Particle size distribution after the microchips grinding experiment.

	Sample 1	Sample 2	Sample 3	Mean %	St. dev.
Total weight (kg)	0.71	0.69	0.73	-	-
Weight (in kg) of particles >10 x 10	0.00	0.00	0.00	0,00%	0,00%
Weight (in kg) of particles >5 x 5	0,40	0.40	0.45	58,65%	2,72%
Weight (in kg) of particles >2,5 x 2,5	0,25	0.26	0.25	35,71%	1,77%
Weight (in kg) of particles < 2,5x2,5	0,06	0.03	0.03	5,64%	2,44%

More specifically, the structural configuration of the grinder was composed by the parts listed in Table 6, with a rotational speed of 4000 rpm, and a mass flow rate of 400 kg/h. Differently from the sawdust production, the mass flow rate sensibly influenced the particle size composition of the microchips.

Errore. L'origine riferimento non è stata trovata.~~Figure 11~~ shows the particle sizes obtained through the sieving of a sample of material before and after being processed by the grinder prototype (it is worth to notice that the figure is not representative of the real percentages that actually constitute the sample). Indeed, bigger particles (>10mm x10mm) were almost absent after grinding with the considered configuration, and all those shown in **Errore. L'origine riferimento non è stata trovata.**~~Figure 11~~ were collected through different samples. The actual percentages of the particle sizes composing the samples after the grinding are shown in Table 6~~Table 5~~ and Figure 12.

Table 6. Rotor and stator stages for the preferred "microchip" configuration of the grinder.

	First rotor stage	Second rotor stage	First stator stage	Second stator stage
Number of blades	6	15	4	13

Figure 11. Particle sizes composing the wood chips before and after grinding with the prototype. The samples have been obtained by selective sieving. Each row represents a specific sieve stage (measures in mm). Note that the particle shown here are not representative of the actual quantities present in the samples. This is especially valid for bigger particles after grinding, which were present in a very few quantity.

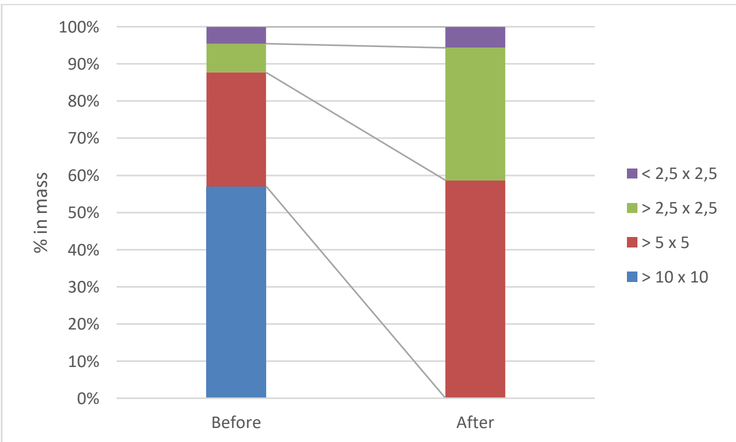

Figure 12. Particle size distribution before and after grinding in the "microchips" configuration.

Comparing the data shown in Table 3 with those of Table 5 (see Figure 12), it is important to observe that the bigger particles (>10 x 10) were almost completely transformed into particles belonging to the range of the two middle sizes, while the percentage of the finer particles remains almost unchanged. More precisely, bigger particles after grinding were very rare, always leading to weights below 0.005 kg and the production of further smaller particles is negligible.

No dehumidification effects have been observed in this case. Eventually, the overall energy consumption for this configuration was of about 9 kWh/tonne (i.e. about 16 kWh per tonne of dry wood), with an airflow rate of about 450 m^3/h.

4 Discussions

4.1 *About the achieved results*

4.1.1 *Sawdust for pellet production*

The performed tests revealed that the prototype, in the specific configuration described in Subsection 3.1, is capable to produce wood sawdust from wet wood chips, directly exploitable for the pellet production process. Indeed, a sample of the produced sawdust has been used to successfully produce pellets.

The grinding energy consumption (47 kWh per tonne of dry wood), if compared with current hammer mills, is promising. Indeed, Masche et al. [30] recently performed a test where Pine and Beech chips were grinded by a series of two hammer mills. For the first hammer mill (screen mesh dimension of 15 mm) they observed a power consumption between 8.1 and 12.6 kWh per tonne of dry wood. Differently, for the second mill (screen mesh dimension of 4 mm), the power consumptions reached values between 43.6 and 49.4 kWh per tonne of dry wood. These data are in line with the study performed by Esteban et al. [31], where a series of two grinders (a rotary knife mill and a hammer mill) processing pine chips with a moisture content between 10% and 15%, led to an overall power consumption between 45 and 53 kWh per tonne of dry wood.

Part of the energy spent by the new proposed system is related to a contextual dehumidification phenomenon, capable to extract the 5% of the wood's moisture content. However, no evident relationships between measured sound pressure levels and dehumidification performances were observed.

Commentato [f4]: Anche perché non abbiamo dispiegato i mezzi per farlo quindi per forza non si poteva osservare. Valutare se togliere questo discorso.

4.1.2 *Microchips*

The tests performed for the production of microchips allowed to identify a specific grinder configuration capable to almost completely eliminate particles bigger than 10 mm but avoiding the production of particles smaller than 2,5 mm in length. Although the considered sieve and the related grids were not exactly compliant with the tests prescribed by certain quality certifications, the obtained data revealed that the grinder is capable to produce particle sizes within the required range. It is important to highlight that the prototype and the experimental plant were not originally thought for the production of this specific biofuel, and therefore the obtained results are highly encouraging. Moreover, the very limited power consumption characterizing the proposed grinder technology allows considering the "chipping + refining" process as a competitive alternative to the current "chipping + sieving". However, more tests focused on the economic feasibility of this alternative should be performed to validate or reject such a hypothesis.

4.2 ***Limits of the prototype, the experimental plant and the instruments***

Both the prototype and the experimental plant were characterized by non-negligible limits, which hindered additional and deeper experiments.

First of all, the need for a soundproof isolation, together with the need of covering the hopper with an airtight lid (see Section 3 for motivations), led to the impossibility of processing high quantities of wood chips continuously. Indeed, once processed the material contained in the hopper, all the plant needed to be stopped to refill it with new wood chips (about 150 kg). It was sufficient for the tests performed in this paper, but durability trials were not possible. Consequently, it was not possible to establish the right material for building the cutting means, the actual maintenance operations and frequencies required in real operation cases (e.g. re-sharpening of blades).

Another important limitation of the experimental plant was the absence of drying systems to measure the actual energy saving derived by drying smaller wood particle sizes. This lack led to the impossibility of performing the measurements required for comprehensively validating the advantages provided by the tested grinder prototype, for both sawdust and microchips production. According to literature, this kind of experiments are critical, because to obtain reliable data for comparison, it is important to correctly consider and set up the design parameters of the dryers [32]. Indeed, Fyhr et al. [13] observed that the drying time can be reduced three times by halving the linear dimensions of the wood particles, but a more recent study executed on smaller particles, although confirming the dependence between size and drying time (and then power consumption), shows a reduced impact [33]. It suggests that the actual advantage from drying smaller particles needs to be investigated in depth.

Concerning microchips production, the limits have been already introduced in Subsection 3.2, and refer to the limited range of grinder's configurations actually available for this specific particle size. Therefore, the preferred configuration identified in Subsection 3.2, although extremely encouraging, could not be the best one actually attainable with this technology.

Moreover, the rudimental sieve adopted in this work hinders comprehensive analysis for particle size distributions. Indeed, no additional mesh size variants are available, thus avoiding the identification of most representative particle sizes. Moreover, the sieving device is manually operated, thus leading to non-repeatable shacking time and movements, which could be a concurrent cause of the non-negligible standard deviation values observed in Table 2, Table 3 and Table 5.

Finally, it was not possible to comprehensively investigate the dehumidification phenomenon observed in the production of wood sawdust. In particular, pressure waves and frequencies were measured only with simple industrial devices capable to deal with the audible spectrum. Consequently, it was not possible to investigate the possible effects of ultrasonic waves.

4.3 ***Hints for future experiments and redesign of the grinder***

Each highlighted limitation constitutes a potential hint for future developments, which however may imply new investments of resources. Indeed, to perform more extended tests about microchips, both the grinder prototype and the experimental plant should be modified to allow further configurations. Therefore, one of the next activities is related to the redesign of the prototype and to the optimization of the experimental plant for microchips production tests. However, it is also necessary to comprehensively characterize the grinding technology, by comparing its performances with acknowledged milling models [34–38]. Nevertheless, the acknowledged theoretical milling models do not consider the effect of the airflow for both power consumptions and particle size reduction, while the airflow is a fundamental parameter in the new proposed grinding technology. A possible hint for future experiments is to extract the net comminution energy consumption, e.g. eliminating fluid-dynamic consumption from the total energy measures, and to compare it with milling theories. In addition, more comprehensive characterizations of the particle size distributions is needed, e.g. with Rosin-Rammler particle size analysis [38–40].

However, it is acknowledged that hammer mills spend more energy when processing moist wood chips [8,41]. It is valid also for different grinding/comminution systems (e.g. wood chippers [42]), but it is not clear whether it fits or not with the new proposed technology. Moreover, for traditional grinders, the grinding energy requirements are sensibly influenced by the wood species [43]. Therefore, specific tests should be performed with the new proposed grinder, to control the effects of the species of wood, particle size reduction rate and moisture content (e.g. as made in [41] for hammer mills).

Additionally, it is important to perform accurate evaluations about the actual advantages derived from drying smaller particles in classic heat-type ovens. It is preferable to perform tests on real scale ovens to identify both advantages and criticalities. The acquisition of a real oven only for this experiments falls out of the available budget limits but the restructuring of the experimental plant to produce higher quantities of material could make possible to negotiate with owners of existing pellet production plants to test their production processes fed with the sawdust produced by the prototype. Similar experiments can be performed to assess the actual benefits provided by producing microchips with the proposed process and technology.

Concerning the dehumidification observed for the sawdust production, several activities are still needed to understand the physical phenomena behind the observed effect. Accordingly, testing campaigns should be performed by focusing on measurements about both the extracted water and the possible effect of ultrasonic pressure waves. For the first purpose, measuring the moisture content of the material before and after grinding is an opportunity, but a continuous measuring system would be preferable, allowing to perform more extended factorial programs of experiments with fewer resources. For the second purpose, high-frequency transducers should be placed within the grinder to verify the actual presence of ultrasonic waves.

Eventually, the new proposed technology could be adapted for other industrial contexts and needs, where the grinding of wood or other material is needed [44]. For example, also the production process of Medium Density Fibreboards (MDF) is characterized by the need of refining and drying wood particles. To this purpose, the existing prototype can be used to perform preliminary comminution tests for other products (e.g. corn for the production of flour, vegetables for the production of infusions, comminution of coffee, etc.).

5 Conclusions

The paper presents a new technology and the related proof of concept prototype for grinding woody biomass. The outcomes of the tests performed on generic samples of wood chips (a mixture mainly composed by chestnut, beech and acacia trees), highlighted the encouraging performance of the new technology for the production processes of both wood pellet and microchips. More specifically, the new grinding system is capable to mill green wood having high moisture contents, without experiencing the problems of the traditional technologies. For the pellet production process, this characteristic allows to consider alternative drying processes directly operating on wet sawdust, with potential benefits in terms of drying energy saving. Moreover, a contextual dehumidification effect of the wood biomass has been also observed when producing sawdust with the grinder prototype. However, to understand this phenomenon, further investigations are needed with instruments capable to measure ultrasonic pressure waves.

For the production of wood microchips, notwithstanding the limitations of the available prototype and plant, the performed tests demonstrated the capability to produce the required particles with a limited power consumption.

However, future research should be performed to better investigate the potentialities of the new technology, as well as its most convenient integration in the industrial processes and the related benefits. Nevertheless, the performed tests demonstrated the feasibility of the system, which actually offers new innovation opportunities for both industry and forestry. Accordingly, the information provided in this paper, besides introducing the potentialities of this new grinding technology, allows both researches and practitioners to reproduce the system for further experiments and investigations.

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