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OPTIMIZATION OF PELLETISATION AND COMBUSTION IN A BOILER OF 17.5 kW_{th} FOR VINE SHOOTS AND INDUSTRIAL CORK RESIDUE

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Abstract

Wood pellets have become an important renewable energy fuel. Nowadays the main raw materials used for their production are wood wastes from wood industries. However, these wood wastes have other uses in Spain and it is necessary to look for other possible raw materials. In this work, vine shoots and industrial cork residue were studied as raw materials. The results showed that pelletisation of vine shoots presented a high energy demand. This energy requirement was reduced with the addition of industrial cork residue. Moreover, industrial cork residue decreased the ash content of pellets and increased their heating value, although it decreased their physical properties at the same time. Regarding combustion, the addition of industrial cork residue decreased the accumulation of ash in the pellet burner and its sintering tendency. The major conclusion of the work is that the most appropriate blend to improve pelletisation and combustion processes is 30% wt. of vine shoots and 70% wt. of industrial cork residue.

Keywords

Combustion, cork, pelletisation, pine sawdust, vine shoots

1. Introduction

Solid biomass is obtained in origin with some characteristics (low bulk and energy density, variable moisture content and heterogeneity) which are not valuable in order to its direct energy utilization. Consequently it is necessary to carry out a previous stage of pretreatment such as drying, milling and pelletisation of the biomass raw materials. Pelletisation could be defined as the physical and chemical transformation, with or without additives, of the lignocellulosic matter with fine granulometry and low density into solids with steady shape and size and high density (pellets) utilizing mechanical pressure [1]. The process of forming biomass pellets depends on the physical properties of ground particles and the process variables during pelletisation, i.e. pressure and temperature. The compaction process is a complex interaction between particles, their constituents and forces [2].

Wood pellets have become a successful fuel for small and medium heating plants, specially in countries from the North and the Centre of Europe (Sweden, Austria and Germany) [3], highlighting the paper of Italy in this sector in the last years. Their success can be explained since they are easy to handle, transport and store due to their uniform size, high density and low moisture content. However, the quality of pellets is determined by the end-user's requirements on the combustion system and the handling properties [4].

In order to define the pellet properties, two groups of variables evaluating its quality are set up: chemical and compositional variables and physical variables. The first group includes criteria such as the concentration of certain elements (Cl, N, S and heavy metals), the ash content, the moisture content, the calorific value and the ash melting behaviour. The physical characteristics listed in the second group describe the visual parameters and the type of processing that the biomass has undergone. The relationship between the measured parameters and their effects is shown in Table 1 and Table 2, which are mainly based on the work of Malisius et al. [5].

Most of the raw material processed by pellet production plants in Spain is wood waste coming from wood processing industries. Those wood wastes are increasingly recycled for energy use in the same processing plants where they are generated. Moreover, wood waste from wood processing industry is a worthy raw material for the particle board manufacturing industries, which constitute an important lobby sector in the country. Consequently, it is necessary to look for alternative raw materials that can be introduced in the pellet markets [6].

In this sense, vine shoots and cork are typical residues in some regions of Portugal and Spain [7] which could contribute to the pellet industry as raw materials. Spain is the country with the highest surface cultivated with vineyards in the world, 8% of the total cultivated area in the country is covered by vineyards (*Vitis Vinifera* L.) [8] which represent a 15% over the total area occupied by vineyards in the world [9]. The cork is harvested exclusively from the cork oak (*Quercus Suber* L.) found predominately in the Mediterranean region and specially in Portugal and Spain where are obtained the highest productions in the world (52% of the world production in Portugal and 32% in Spain) [10].

The objectives of this work are to evaluate the pelletisation of vine shoots, industrial cork residue and some blends of these materials, as well as the characteristics of the pellets obtained in order to define their quality as fuels; to study their combustion in a small boiler (17.5 kW_{th}); and to compare the obtained results to those achieved in a similar process with pine sawdust, which is used as reference material in the pelletisation and in the combustion processes.

2. Experimental

2.1 Biomass raw materials

The biomass materials were collected in the following locations:

- The vine shoots (*Vitis Vinifera* L.) was obtained in Navarra (Northern Spain).
- The industrial cork residue was received from Portugal.
- The pine sawdust (*Pinus Pinaster* Ait.) was gathered from a sawmill from Castilla y León (Central Spain).

2.2 Comminution equipment

The comminution of the vine shoots was carried out with three machines:

- A double axis shredder with 22 kW drive power.
- A primary crusher which was a double bearing horizontal axis knife mill with a drive of 35 kW power and 640 r.p.m. rotation speed. The exchangeable insert screen had an opening in the upper part to feed the material into the chamber perpendicularly to the rotor axis. The rotor carried nine

knives and two counter-knives that reached a peripheral velocity of 20 m s^{-1}. The inner diameter of the grinding chamber was 600 mm.

- A secondary grinder which was a single bearing horizontal axis hammer mill with a drive of 11 kW power and 3000 r.p.m. rotation speed. The grinding chamber was surrounded by a closed exchangeable perforated screen with an inner diameter of 485 mm. The feeding of the biomass was from the front side of the chamber, parallel to the rotor axis. The number of hammers was 24 and the peripheral velocity was 71 m s^{-1}.

2.3 Pellet plant

The facility used in the experiments was a pellet pilot plant (Figure 1) which included a blending system, a pellet mill and cooling and bagging equipment. The pellet press had a flat die type Amandus Kahl 33-500: die diameter 500 mm, roller width 75 mm, drive power 30 kW. The press was equipped with a hydraulic pressure system able to generate a pressure up to 110 bar.

2.4 Pellet boiler

The boiler utilised in the combustion tests was a commercial household boiler with a nominal thermal capacity of 17.5 kW specially designed for combustion of 6 mm diameter pellets (Figure 2). Combustion of pellets took place on a basket with a cross section of 21 cm x 5cm, which was perforated at the bottom with 62 holes of 5 mm of diameter and at two sides with 9 and 4 holes of 4 mm of diameter; through these holes, the combustion air was introduced.

The combustion was started by hot air from an electrical resistance located close to the burner. The pellets were manually loaded into a hopper (with capacity for 30 kg of pellets) and they were fed to the burner by means of an intermittently moved screw conveyor placed at the top of the burner. The pellet feed rate could be manually regulated on a scale from 0 to 10. The primary combustion air was introduced through an inlet beside the burner and when the combustion ran properly, the ashes were elutriated by the combustion air from the burner to the ash pan through a grate. A fan was used to extract the combustion fumes, crossing the heat exchanger, which consisted of 38 vertical pipes surrounded by water, and crossing two lateral chambers to the chimney. The extraction rate could be manually regulated on a scale from -9 to 9 or programmed in automatic mode (recommended by manufacturer).

This type of boilers has a very simple mechanism of work and this aspect determines that the utilised pellets must have a high quality with low content in ashes in order to achieve an appropriate operation of the boiler. On the other hand, these boilers are cheaper compared to other more sophisticated boilers (with secondary and tertiary combustion air, lambda probe, cleaning systems in pipes and burner...) and their use is very widespread.

2.5 Experimental design

The most appropriate screen size for milling vine shoots for the pelletisation was 4 mm according to a previous work [11]. A scheme of the material preparation was the following: firstly, a batch of 1000 kg of air dried vine shoots was crushed in the shredder and subsequently it was cut in the knife mill, where an insert screen of 10 mm opening was utilized. Next, the batch was ground to pass a 4 mm screen using the hammer mill.

Industrial cork residue and pine sawdust showed a suitable size for their pelletisation when they were received and milling was not necessary. Particle size distribution of the different raw materials is shown at Figure 3. Pine sawdust and vine shoots with similar particle size distributions had been pelletised successfully in a previous work [11] and it can be observed that particle size distribution of industrial cork residue is comparable to values obtained for 4 mm milled vine shoots and pine sawdust. Moisture content of cork was appropriate as received (10 %) and pine sawdust was dried in a rotary dryer.

The raw materials and blends utilized during pelletising tests were the following:

- Vine shoots (VS)
- Industrial cork residue (ICR)
- Pine sawdust (PS)
- Blends of vine shoots and industrial cork residue:
    - 40% wt ICR with 60% wt VS.
    - 50% wt ICR with 50% wt VS.
    - 60% wt ICR with 40% wt VS.
    - 70% wt ICR with 30% wt VS.

Pelletising tests were carried out with the same rollers (75 mm width) and different die compression: milled vine shoots, industrial cork residue and their blends were pelletised with a die compression of 20 mm; meanwhile for pine sawdust a die compression of 24 mm was necessary to obtain an adequate pellet quality, as it was tested in a previous work [11]. The same hole diameter at dies was used in all tests (6 mm). The die compression (pressway) is defined as the way between the beginning of the inlet cone and the end of the straight part of the die hole (Figure 4). During pelletising tests, batches of 300 kg of raw material were put in the pellet press mixed with the suitable quantity of water in order to pelletise for 2 hours. After pelletising process, 50 kg of each type of pellets were seized to be utilized in combustion tests and they were selected by means of quartering method (this method reduces a sample by successively mixing, dividing into quarters and keeping two opposite quarters of the sample). From these 50 kg, a quantity of 5 kg was separated by quartering method again in order to be physically and chemically characterized at laboratory.

The process variables recorded in the milling and the pelletising tests were the specific mass flow (in kg of dry matter/h kW of drive power) and the specific energy (in kWh/t of dry matter). Specific mass flow is calculated as the mass of milled material or pellets obtained after finishing the whole milling or pelletising process (in kilograms of dry matter) divided by the time utilized to mill or to pelletise (in hours) and by the power of the different mills (knife mill: 35 kW; hammer mill: 11 kW) or the pellet press (30 kW). On the other hand, specific energy is calculated as the energy required to mill or to pelletise the materials by the different mechanical systems contained at the milling plant or at the pellet plant divided by the mass of milled material or pellets obtained after finishing the whole milling process or the whole pelletising process (in tons of dry matter).

Combustion tests had a duration of 10 hours and the emissions from the boiler, the slag formation and the content of unburnt matter in the ashes were studied. During the tests, the boiler burner was fed with the proper mass flow of pellets in order to work next to nominal power and the control of the primary air was programmed in automatic mode to simulate the operation conditions by a common user. At automatic mode, the boiler works with a preset primary air flow for each level of pellets feeding flow. The level of pellets feeding flow was the maximum level permitted by the boiler which corresponded to the highest velocity of the fumes extraction fan. When the combustion finished, the ashes were gathered from five locations: ash pan (A), pellet burner (B), deposits in tubes and internal boiler walls (C), fly ash settled between the heat exchanger and the stack (D) and chimney particles (E) (see Figure 2). Deposits in tubes and internal boiler walls were extracted utilizing a brush; fly ash settled between the heat exchanger and the stack was collected at the outlet of the heat exchanger pipes, at lateral chambers of the boiler between the heat exchanger and the fan and at the bottom of the stack; and finally, chimney particles were collected on a filter utilizing gravimetric analysis.

The process variables recorded in the combustion tests were: operation time allowed by the pellets (limited by the ash accumulation and the slag formation in the pellet burner), temperature inside the pellet burner, emissions (O_2, CO, NO and particles), ash mass distribution after combustion, unburnt mass content in the ashes and visual characterization of the gathered slag.

2.6 Analytical procedures

The utilised analytical procedures were based on extensive investigations, standards and scientific literature. The methods utilised for physical characterization are resumed as follows:

Particle size distribution: this test consisted of the separation of the sample into defined size fractions that were expressed in weight percent. This procedure was adapted from the norm ASTM E 828-81 "Designating the size of refuse derived fuel-3 from its sieve analysis".

Bulk density: the procedure was adapted from the norm ASTM E 873-82. “Bulk density of densified particulate biomass fuels”.

Particle density: it was calculated by means of the ratio between pellet weight and pellet volume, which was determined using the geometrical measures with the help of a caliber.

Durability: this analysis evaluates the resistance of the densified biomass to repeated beating (transport and handling). The determination was made according to the Austrian norm ÖNORM M7134. A machine called “lignotester”, which functions by blowing air at 70 mbar into a pellet chamber, was utilised for determining the durability in pellets. The durability is defined as the final weight of pellets that remains in the pellet chamber divided by the initial weight and multiplied by 100, to express it in percentage.

Calorific value, volatile matter, ash at 550ºC, moisture content, ultimate analysis (C, H and N) measurements were mainly based on A.S.T.M. norms for wood, refuse derived fuels and coal. Chlorine and sulphur analysis was carried out by ionic chromatography after combustion of the sample in a calorimeter and lixiviation of the ashes with ultrapure water.

Chemical analyses of the following elements: Al, Ba, Ca, Fe, K, Mg, Mn, Na, P, S, Si, Sr, Ti and Zn contained in the biomass ash samples (550ºC) were carried out by atomic emission spectrometry (ICP) using a Thermo Jarrell Ash (IRIS AP) simultaneous spectrometer, after digestion of the samples in closed vessel.

Ash fusibility was based on the changes in shape detected during the heating of a cylindrical pellet of ash produced at 550 ºC from room temperature to 1400 ºC. The atmosphere was air. The instrument utilised was an optical heating microscope (LEICA).

O_2, CO, CO_2 and NO emitted during the combustion tests were measured with a continuous analyser using an ABB equipment and particle content in the flue gases was determined by a gravimetric analysis after pseudo-isokinetic sampling.

Unburnt content was determined as the difference between 100% and the ash content obtained from the gathered ash heated at 550 ºC.

3. Results and discussion

3.1 Comminution tests

Vine shoots milling behaviour is characterized by two process variables (Section 2.5), the specific mass flow and the specific energy, whose values are shown in Table 3.

As can be seen in Table 3, the total energy required for milling vine shoots to pass a 4 mm sieve reaches 144 kWh/t (98 kWh/t in the knife mill and 46 kWh/t in the hammer mill). In contrast, industrial cork residue and pine sawdust do not require previous comminution and therefore no energy is consumed for this purpose.

3.2 Pelletising tests

During the tests, raw materials are introduced into the pellet press mixed with a suitable quantity of water, which must be enough to soften the material regarding its way through the die. Another purpose of adding water is to reach a right operation of the pellet press, i .e. without power peaks and without vibration. However this quantity of water must not be too high in order to avoid bad quality pellets easily disintegrated under handling and transport. Values of moisture content of biomass at press inlet change between 11 and 25%, being the lowest data for pine sawdust (11%) and vine shoots (15%) and the highest values for industrial cork residue (22%) and its blends with vine shoots (17-25%). The higher moisture content of cork residue and its blends is a consequence of a higher addition of water to decrease the resistance to compression [12] and to counteract the evaporation in the pellet press. This evaporation is mainly caused by two reasons:

- The high resistance to movement which offers the cork against surfaces, which increases with the roughness of the counter surfaces and gives cork its anti-slippery character [13], [14].
- The low permeability of cork which is due to its high content of suberin [15]. Classically, suberin was defined as an aliphatic substance that was found to be a polyester with long-chain fatty acids [16].

The values of specific mass flow and specific energy appear in Table 4. Milling specific energy for the different blends has been calculated considering the percentage of vine shoots contained in the blend and the specific energy necessary to mill vine shoots, because industrial cork reside included in the blend does not require milling. The results indicate that the specific mass flow in pelletising tests is higher for vine shoots and its blends with industrial cork residue than for industrial cork residue and pine sawdust. Mass flow is higher for blends with industrial cork residue than for vine shoots without blending and it could be explained because the pellet press works better blending vine shoots and industrial cork residue than utilising one of these raw materials alone, as can be seen in the reduction of the specific energy when the percentage of industrial cork residue is increased. This fact could be explained because cork is a flexible material, which is due to its high content in suberin [15], and consequently pressure on the material applied by the rollers is lower than for vine shoots or pine sawdust, as can be seen in Table 4, where the specific energy for pelletising industrial cork residue is 121 kWh/t versus 169 and 166 kWh/t for vine shoots and pine sawdust respectively. Furthermore, the blend with vine shoots increases the bulk density of cork and a higher flow of material is pushed by the rollers through the die. Subsequently, in the tested blends, vine shoots increase the density of the material and industrial cork residue facilitates the compression by the rollers. According to the specific energy, the highest overall value (milling plus pelletising) corresponds to vine shoots, as a consequence of the need of a fine milling.

3.3 Physical and chemical characterization of pellets

Physical characteristics of pellets are shown in Table 5. Moisture contents vary between 9.3 and 12.5%. These values can fulfil the limits given in the norms from Austria (ÖNORM M 7135), Sweden (SS 18 71 20) and Germany (DIN 51731/ DIN plus) in which moisture contents between 10 and 12% are considered as the more convenient; on the other hand, in norm CEN/TS 14961:2005 10% moisture content is considered as the upper limit for high quality pellets [17].

In Table 5, it can be observed that the best quality pellets are those made with vine shoots, as they have the highest values in bulk density, particle density and durability. Furthermore, these characteristics are similar to those of pine sawdust (reference material). The worst quality pellets are those obtained from industrial cork residue which show the lowest values for bulk density, particle density and durability. For the blends made with vine shoots and industrial cork residue, a general pattern is that bulk density and particle density decrease when industrial cork residue percentage increases, which can be explained by the low bulk density of the industrial cork residue (Table 6). However, the differences regarding durability for the pellets made of cork residue and vine shoots blends are not important. An explanation of the lack of correlation between particle density and durability is given by Obernberger and Thek [18], who have demonstrated that these variables are correlated only when pellets are produced under similar conditions and same raw materials.

Samples of each biomass were analyzed and their chemical characterization is shown in Table 7. As can be observed in this Table, ash content of industrial cork residue is lower than ash content of vine shoots, and both of them are very high compared to pine sawdust ash content. Otherwise, volatile matter contained in pine sawdust is higher than volatile matter in vine shoots and industrial cork residue. Regarding elemental analysis, the highest value of carbon content is found in cork residue, followed by pine sawdust and finally vine shoots. This tendency is also observed for the calorific value. In general, the higher the carbon content is, the higher the calorific value.

Sulphur content shows the highest value in vine shoots and, and compared to European norms about pellets quality, this value would be acceptable in norms from Sweden (SS 18 71 20) and Germany (DIN 51731) and in CEN/TS 14961:2005, but not from Austria (ÖNORM M 7135) (the limit in this norm is 0.04%). Nitrogen content in the different analysed materials is higher than the limits in norms from Austria (ÖNORM M 7135) and Germany (DIN 51731) and it exceeds the value for the best quality pellets in CEN/TS 14961:2005. According to chlorine content, vine shoots and pine sawdust are below limits in norms from Austria (ÖNORM M 7135), Sweden (SS 18 71 20) and Germany (DIN 51731); however, chlorine content in industrial cork residue is above the limits in the three countries [17].

The ash composition is characterized by a high content in SiO_2, especially in vine shoots.

Fusibility temperatures are similar for vine shoots and pine sawdust and, according to the values shown in Table 7, these materials would begin to melt around 1220 ºC. Nevertheless, industrial cork residue shows fusibility temperatures higher than 1400 ºC, and this value indicates that this material has the lower sintering tendency.

3.4 Combustion tests

All the combustion tests were programmed for 10 hours, but this duration was lower in some tests due to the ash accumulation and the slagging at the pellet burner as can be seen in Table 8. During the tests, in order to work next to nominal power, the boiler was fed with a mass flow around 2.5 kg/h.

Vine shoots pellets generate ash accumulation and formation of slag at the pellet burner. This causes a poor combustion quality and a final breakdown of the boiler in a short period of time. The addition of industrial cork residue to vine shoots increases the length of the tests, decreasing the ash accumulation and the slag formation. The most appropriate blend has been 30% vine shoots and 70% industrial cork residue. This blend produces a slight accumulation at the pellet burner (see Figure 5) but this small accumulation does not entail a poor combustion.

According to fusibility temperatures (Table 7), vine shoots and pine sawdust should show the same sintering tendency. Nevertheless, vine shoots combustion causes sinter and slag formation and pine sawdust does not show this problem during its combustion. This fact could be explained by the difference of ash content between the two materials, which is 7.1% in vine shoots and 0.9% in pine sawdust (Table 7).

When combustion temperatures are evaluated (Table 8), it can be observed that average temperature in the burner is not available for vine shoots and blends with 60%, 50% and 40% of vine shoots, because the temperature in these tests exceeds quickly 1100 ºC (maximum temperature for the measurement device utilised). This fact is caused by the ash accumulation, which brings about a bad release of heat by the primary air and subsequently the temperature in pellet burner increases up to the levels of ash sintering and even ash slagging.

3.4.1 Emissions and combustion products

During the stationary period of the combustion tests, oxygen concentration values in flue gases are comprised between 12 and 16 % (Table 9), corresponding the highest value to industrial cork residue pellets. This high air excess is caused by the very low density of cork residue pellets (Table 5). In the boiler utilised, the flow of air is only related to the volumetric feed of pellets which is provided by the boiler screw without manual adjustment.

In Table 9 average values for emissions during the stationary period are shown. For vine shoots pellets, these values are an average of all the operation time, because stationary period cannot be considered.

Combustion of vine shoots pellets produces the highest value for emission of carbon monoxide and this can be explained by the ash accumulation and the slag formation in the burner which are the most severe among the different tests (the operation time is the shortest, see Table 8). Industrial cork residue pellets produce lower carbon monoxide emission compared to vine shoots, but it is much higher than for pine sawdust (Table 9). When industrial cork residue is added to vine shoots, carbon monoxide emission decreases compared to vine shoot pellets combustion because ash accumulation in pellet burner decreases according to Figure 5. Furthermore, the combustion of pellets made of 30% of vine shoots and 70% of industrial cork residue, emits less carbon monoxide than industrial cork residue pellets, due to the higher bulk and particle densities of pellets made of blend (Table 5).

According to nitrogen monoxide, the highest value is emitted by the combustion of industrial cork residue pellets, followed by the blends, the vine shoots pellets and finally the pine sawdust pellets. Nitrogen oxides emission depends on nitrogen content in fuel and it increases with this content and with oxygen concentration during the combustion [19]. Nitrogen content is higher for industrial cork residue than for the rest of the raw materials (Table 7), but this difference is not very significant. Consequently, the high difference in emissions of nitrogen monoxide is probably a consequence of the difference of temperature at the burner, which shows the highest value during the combustion of industrial cork residue pellets (Table 8), considering the available temperatures.

Emission of particles is high for industrial cork residue and its blends compared to pine sawdust, the value for vine shoots is not available due to the short length of this test. The elevated value obtained in the combustion of industrial cork residue pellets is mainly caused by the higher ash content of these pellets and possibly the higher fumes convective flow in this test, which generates a dragging of fly ash as consequence of the air excess (Table 9). Another factor could be the lower pellet particle density of industrial cork residue (Table 5). It can be noticed that when industrial cork residue is added to vine shoots, a trend to decrease in the emission of particles is observed when the percentage of industrial cork residue is increased in the blends, probably as a consequence of the lower ash content of the industrial cork residue compared to the vine shoots (Table 7).

As described in Material and Methods, ashes were sampled at five places: ash pan, pellet burner, deposits in tubes and walls, fly ash and chimney particles. Figure 5 shows a diagram where the percentage of ashes in the different sections (calculated regarding the total mass of ashes gathered) is represented for each combustion test.

A general trend is observed in this Figure 5. When the industrial cork residue percentage increases, the percentage of ash gathered in the ash pan increases at the same time that the percentage of fly ash increases and the percentage of ash in the pellet burner decreases. This fact is explained by the dilution of the ash elements responsible of the accumulation and sintering phenomena. Consequently, the ash which is not accumulated in the burner, is mainly gathered in the ash pan and as fly ash. Furthermore the addition of industrial cork residue could increase the percentage of fly ash as consequence of its low density compared to vine shoots (Table 6).

Unburnt content from the gathered ash in the different boiler locations is shown in Table 10. In general, it can be noticed that the highest unburnt content is for chimney particles, but it must be considered that the percentage of ash emitted by chimney is low (less than 12% wt. of the total ash collected). It can be emphasized the high unburnt content for pine sawdust ashes as well, but these values are not significant taking into account the low ash content in pine sawdust (0.9 % wt.) (Table 7).

4. Conclusions

The conclusions from the present work were that the addition of industrial cork residue to vine shoots in order to obtain pellets, improved the pelletization process and decreased the total energy demanded (these decreases in the energy demanded were from 20% for the blend with 40% wt. of industrial cork residue to 52% for the blend: with 70% wt. of industrial cork residue). At the same time, the addition of cork residue decreased the ash content of the pellets obtained and increased their heating value, but, however, it decreased their physical quality. Regarding combustion tests, with the addition of industrial cork residue to vine shoots, the trend of the ash to accumulate and to sinter in the pellet burner was reduced and the time before the breakdown of the boiler was increased. Carbon monoxide emission was reduced respect to emission from combustion of vine shoots, as well.

Considering the pelletization and combustion processes, the most appropriate percentage of industrial cork residue to add to vine shoots was 70% wt. With the addition of this percentage, the physical quality of the obtained pellets was acceptable. Furthermore, according to combustion tests, pellets with 70% wt. of cork residue had a suitable behaviour in order to operate during ten consecutive hours in a boiler with a very simple work mechanism without problems of accumulation and sintering of ashes.

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FIGURES

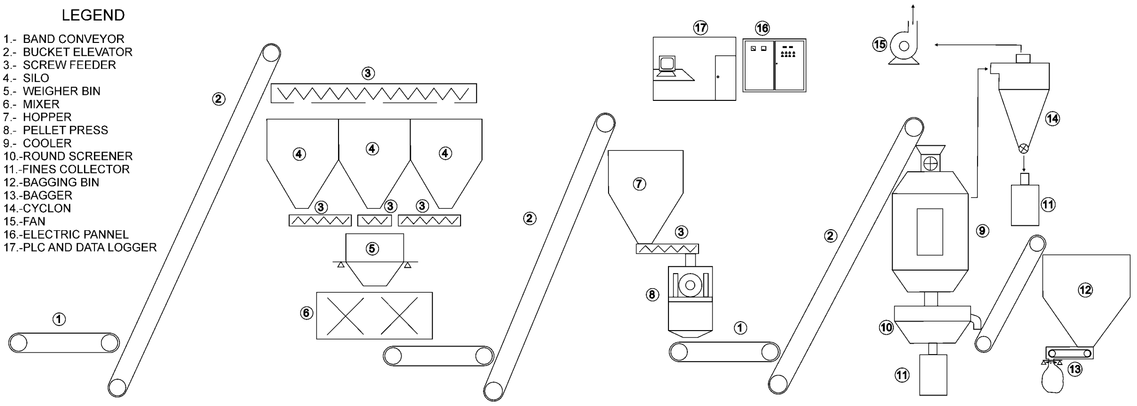

Figure 1: Layout of the pilot pellet plant used in the experiments located at CEDER-CIEMAT

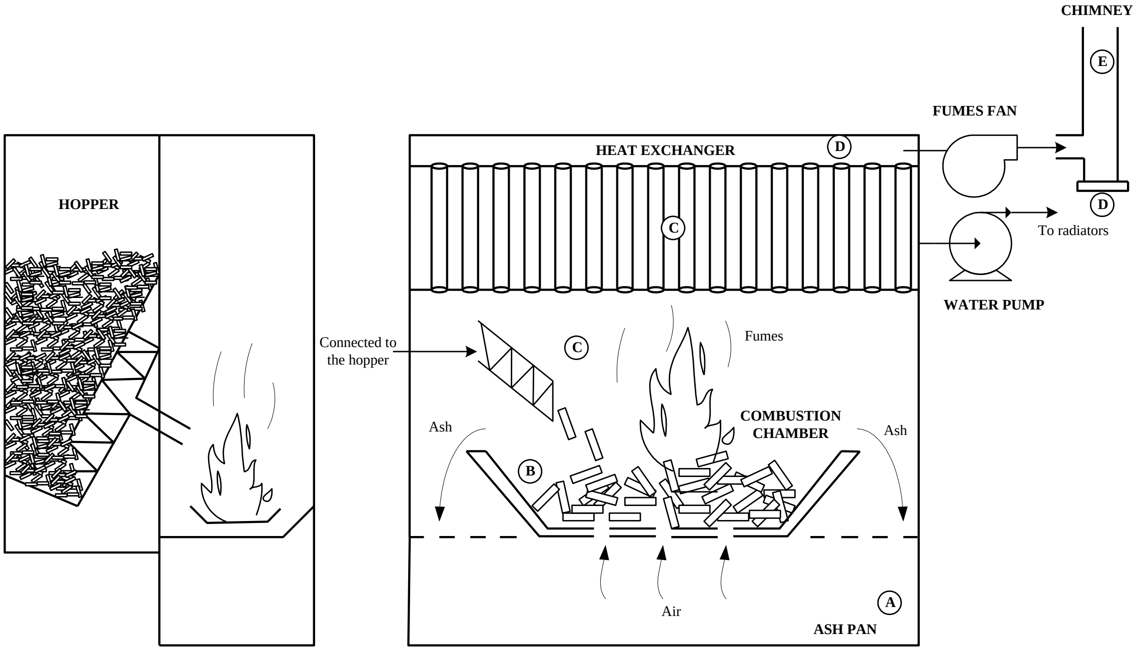

Figure 2: Diagram of the pellet boiler located at CEDER-CIEMAT

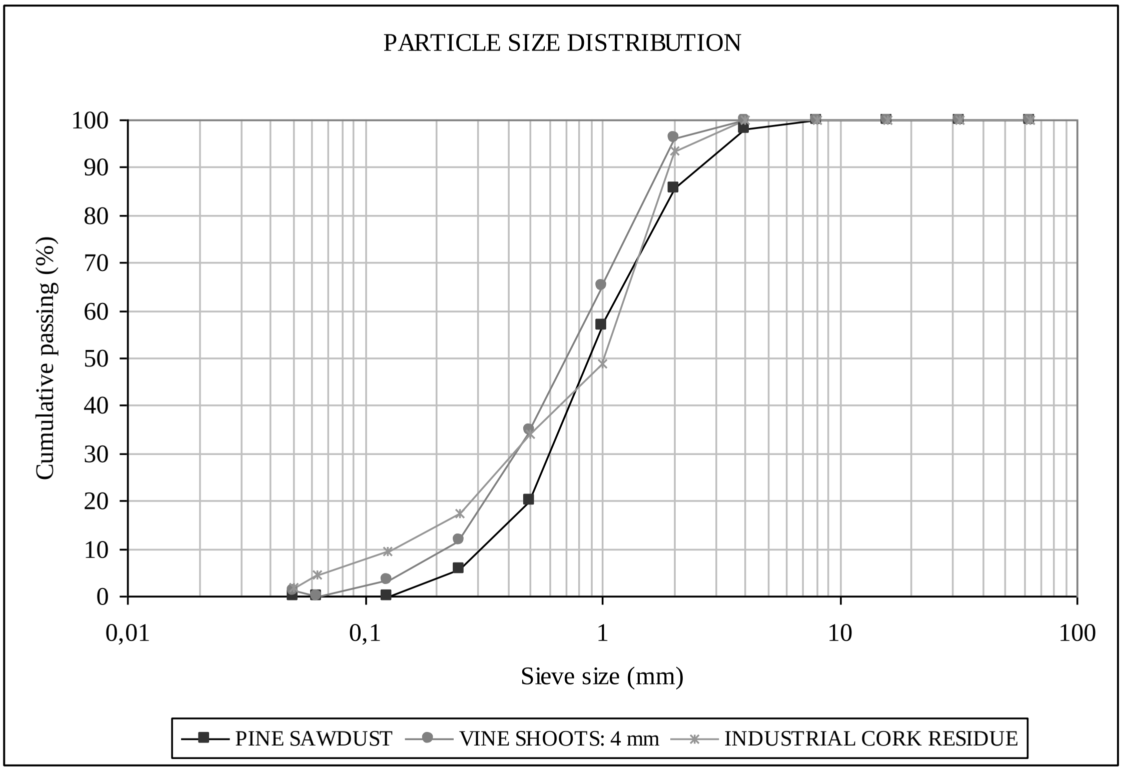

Figure 3: Particle size distributions of the different raw materials

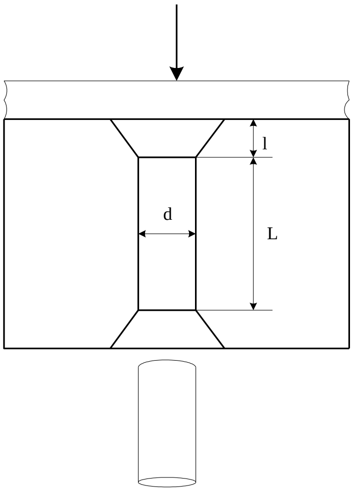

Figure 4: Die compression = l + L

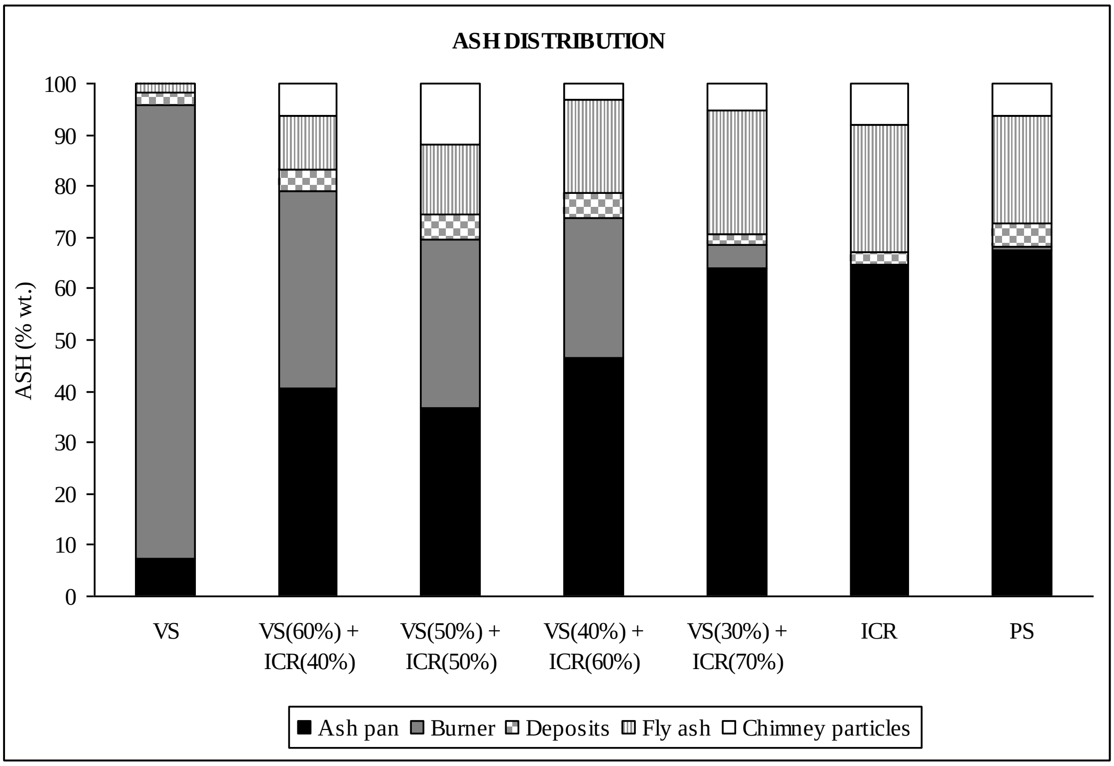

Figure 5: Ash distribution diagram of the combustion tests

TABLES

Table 1: Quality characteristics of pellets: Chemical and compositional characteristics

Parameter	Effects
Moisture content	Storability, calorific value, losses, self-ignition.
Calorific value	Fuel utlilization, plant design.
Cl	HCl, dioxin/furane emissions, corrosion in superheaters.
N	NO_x emissions.
S	SO_x emissions.
K	Corrosion in superheaters, reduction of ash melting point
Mg, Ca, P	Raising of ash melting point, effect on pollutant retention in ashes and use of ashes
Heavy metals	Pollutant emissions, use or disposal of ashes.
Ash content	Particle emissions, costs for use or disposal of ashes.
Ash melting behaviour	Operational costs, reduction of thermal efficiency, non-programmed shutdowns.

Table 2: Quality characteristics of pellets: Physical characteristics

Parameter	Effects
Bulk density	Transport and storage expenditures, storage volume, logistical planning
Particle density	Combustion properties
Particle size distribution	Brigde-building tendency, operational safety during fuel conveying, drying properties, dust formation
Share of fines	Transportation losses, dust formation
Mechanical durability	Disintegration during transport, fuel losses

Table 3: Specific mass flow and specific energy in milling for vine shoots

Inlet material	Screen pore size (mm)	Specific mass flow (dry kg/h kW)	Specific energy (kWh/dry t)
Shoots	10	11	98
Product crushed (10 mm)	4	26	46

The values of the specific mass flow for the screen pore size of 10 mm are related to the knife mill throughput and the values for 4 mm are referred to the hammer mill throughput.

Table 4: Specific mass flow and specific energy in pelletising and total specific energy utilised

Raw material	Pelletising Specific mass flow (dry kg/h kW)	Specific energy (kWh/dry t)	Milling + Pelletising Specific energy (kWh/dry t)
VS	4.4	169	313
VS (60%) + ICR (40%)	4.4	163	250
VS (50%) + ICR (50%)	4.8	145	217
VS (40%) + ICR (60%)	4.7	130	188
VS (30%) + ICR (70%)	5.0	107	150
ICR	3.9	121	121
PS	3.8	166	166

Table 5: Physical characteristics of pellets

Raw material	Moisture content (wt. %) (w.b.)	Bulk density (kg/m^3) (w.m.)	Particle density (kg/m^3) (w.m.)	Durability (wt. %) (w.m.)
VS	10.8	700	1250	98.8
VS (60%) + ICR (40%)	12.5	560	1110	96.6
VS (50%) + ICR (50%)	10.4	530	1030	97.7
VS (40%) + ICR (60%)	9.6	500	1000	96.5
VS (30%) + ICR (70%)	9.5	500	950	96.2
ICR	10.1	400	780	90.2
PS	9.3	650	1210	98.2

wt %: weight %; w.b.: wet basis; w.m.: wet matter

Table 6: Bulk density of raw materials

Raw material	Bulk density (dry kg/m^3)
Milled vine shoots (4 mm)	270
Industrial cork residue	190
Pine sawdust	210

Table 7: Chemical and physical characterization of the biomass materials

	Unit	Vine shoots	Industrial cork residue	Pine sawdust
Calorific values				
HHV	MJ/kg d.m.	18.7	21.9	20.8
LHV	MJ/kg d.m.	17.5	20.6	19.5
Proximate analysis				
Ash	wt.% d.b.	7.1	4.4	0.9
Volatile matter	wt.% d.b.	74.7	74.7	83.6
Ultimate analysis				
Carbon	wt.% d.b.	46.9	52.0	50.5
Hydrogen	wt.% d.b.	5.7	6.0	6.1
Nitrogen	wt.% d.b.	0.58	0.61	0.48
Sulphur	wt.% d.b.	0.05	0.03	0.03
Chlorine	wt.% d.b.	0.01	0.06	0.01
Ash composition				
Al_2O_3	wt.% d.b.	4.9	1.7	2.4
BaO	wt.% d.b.	0.022	0.069	0.047
CaO	wt.% d.b.	22	38	26
Fe_2O_3	wt.% d.b.	2.3	0.96	8.5
K_2O	wt.% d.b.	8.6	6.7	7.6
MgO	wt.% d.b.	2.4	1.5	6.1
Mn_2O_3	wt.% d.b.	0.12	0.46	1.1
Na_2O	wt.% d.b.	0.38	0.72	0.60
P_2O_5	wt.% d.b.	3.4	1.5	1.5
SO_3	wt.% d.b.	1.5	1.8	15
SiO_2	wt.% d.b.	44	18	31
SrO	wt.% d.b.	0.083	0.14	0.036
TiO_2	wt.% d.b.	0.26	0.078	0.12
ZnO	wt.% d.b.	0.043	0.026	0.11
Fusibility temperatures				
Initial deformation	ºC	1230	> 1400	1220
Sphere	ºC	n.d.	> 1400	n.d.
Hemisphere	ºC	1270	> 1400	1250
Fluid	ºC	1280	> 1400	1260

wt %: weight %; d.b.: dry basis; HHV: higher heating value; LHV: lower heating value; n.d.: not detected

Table 8: Operation time, ash accumulation and sinter formation at the pellet burner and average temperature in the burner

Raw material	Time (h)	Ash accumulation	Sinter formation	Burner temperature (ºC)
VS	1.4	Yes	Yes	n.a.
VS (60%) + ICR (40%)	3.5	Yes	Yes	n.a.
VS (50%) + ICR (50%)	3.9	Yes	Yes	n.a.
VS (40%) + ICR (60%)	8.2	Yes	Yes	n.a.
VS (30%) + ICR (70%)	10	Yes	No	750
ICR	10	No	No	820
PS	10	No	No	770

n.a.: not available

Table 9: Average values for emissions during the stationary period referred to dry basis and reference oxygen of 10% (v%)

Raw material	O_2 (v %)	CO (mg/Nm^3)	NO (mg/Nm^3)	Particles (mg/Nm^3)
VS	12.6	9000	260	n.a.
VS (60%) + ICR (40%)	14.6	7100	330	330
VS (50%) + ICR (50%)	12.9	5000	330	320
VS (40%) + ICR (60%)	13.4	3400	320	280
VS (30%) + ICR (70%)	14.3	1700	310	210
ICR	15.6	3100	470	300
PS	12.4	600	100	50

v %: volume %; n.a.: not available

Table 10: Unburnt content in ashes

Raw material	Ash pan (% wt.)	Burner (% wt.)	Deposits (% wt.)	Flying ash (% wt.)	Chimney particles (% wt.)
VS	13.0	1.0	7.7	18.9	n.a.
VS (60%) + ICR (40%)	10.6	1.9	19.8	3.9	24.9
VS (50%) + ICR (50%)	1.7	0.0	14.9	0.9	23.3
VS (40%) + ICR (60%)	0.1	0.0	12.0	0.8	13.6
VS (30%) + ICR (70%)	0.0	0.0	4.3	0.0	14.3
ICR	0.0	0.0	6.1	0.0	20.2
PS	32.2	0.0	18.0	22.8	15.0

wt %: weight %; n.a.: not available