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MANUFACTURING OF TORREFIED PELLETS WITHOUT A BINDER FROM DIFFERENT RAW WOOD MATERIALS IN THE PILOT PLANT

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ABSTRACT

This paper concentrated on the production of torrefied without an additional binder from different raw wood materials. The torrefaction and pelletizing was carried out at the Torrec Ltd. pilot plant located in Eastern Finland and its effective capacity was 2,200 tonnes per year. Six different woodchips lots were tested in the pilot runs. The test was to identify whether the pelletizing process requires an additional sealant as a binder. The pelletizing process only exploited condensation water that came about from the torrefaction process. The temperature control range and the holding time were varied, regarding the driving parameters. Finally, quality factors were analysed from torrefied pellets and its raw wood materials after each pilot run. The maximum temperature of the reactor, 260°C, was perhaps too low to manufacture pellets of high energy content. Based on the study, the pelletizing process will not require an additional binder in the future.

KEYWORDS: Torrefaction, pellet, binder, quality, biomass, woodchips.

INTRODUCTION

Torrefaction means a thermo chemical treatment of wood at 200 to 320°C and the process takes place in oxygen free circumstances. At this point, the temperature is high enough to evaporate the water from inside the wood, and then the moisture content (MC) of the wood achieves an almost zero point. Wood is completely dried during the torrefaction and the absorption of water is very minor, when the process is over. The MC varies from 1 to 6 w-%, depending on the torrefaction conditions and the treatment of the product afterwards (Bergman 2005). A torrefied wood pellet is an effortless end product, as the handling and transportation of pellets is economical, whilst, it also has a high energy density of>3.9 $MWh.m^{-3}$ (bulk) (Pöyry 2011). Energy density for regular wood pellet remains significantly less, at only 2.8 – 3.3 $MWh.m^{-3}$ (bulk). As a consequence of these values, the energy content per volume is 20 – 40% higher for torrefied wood pellets than for regular wood pellets. In addition to the high energy density of torrefied pellets, they have a high calorific value of between 20 - 23 $MJ.kg^{-1}$. It is noteworthy that the properties of charcoal are almost the same as the chemical and physical features of torrefied material. Co-firing with torrefied pellets offers the significant additional advantages of using existing coal-fired power facilities, reducing the need for new capital investment, and diminishing greenhouse gas emissions (Wolfgang 2012).

The high temperature of the torrefaction process improves the heating charcoal value of wood. Tab. 1 shows the effect of the torrefaction temperatures on the heating values of wood (Baltic Bioenergy). Wei-Hsin et al. (2011) demonstrated in the study that the process temperature of 280°C increased the calorific value of the wood by 40%. On the other hand, the mass loss of the wood was over 50%. The study proved that a process temperature of 250°C, along with a torrefaction time longer than one hour, was the recommended procedure to improve the value and grindability, at the same time as avoiding too high a mass loss of the wood.

Tab. 1: Typical calorific values for untreated wood, torrefied wood and coal (Baltic Bioenergy 2016).

Material	Processing temperature (°C)	Heating value ($MJ.kg^{-1}$)
Untreated wood		18.0
Torrefied wood	230	18.5
	250	19.0
	280	22.0
Coal		15.0 - 31.0

There is a desire to increase the use of torrefied pellets and to standardize the variable methods, and because of this, there are plans to draft a new product standard in Europe, as well as a worldwide standard in the sector project. The European and International Standard will be developed parallel to each other and the European torrefied pellet will belong, according to the quality criterion, to the EN ISO 17225-8 standard for “Graded thermally treated and densified biomass fuels” (Alakangas 2014a). Tab. 2 shows the quality criterion of torrefied pellets, according to the new product standard. Thermal treatment contains the following processes: torrefaction, charring, steam explosion, and hydrothermal carbonization. All of these processes are more or less contacted to oxygen, heat, water and steam. According to the ISO 16559:2014 standard, a thermally woody treated biomass is defined as a biomass, whose chemical composition has been changed by the effect of heat.

Tab. 2: Quality criterion of torrefied pellets under the new EN ISO 17225-8 standard (Alakangas 2014a). The pellets are divided into three different quality classes.

Property class	Unit	TW1	TW2	TW3
Diameter, D	(mm)	D06, 6 ± 1 D08, 8 ± 1	D06, 6 ± 1 D08, 8 ± 1	D06, 6 ± 1 D08, 8 ± 1
Length, L	(mm)	3.15 ≤ L ≤ 40	3.15 ≤ L ≤ 40	3.15 ≤ L ≤ 40
Moisture, M	(%), as received, wet basis	M08 ≤ 8	M08 ≤ 8	M08 ≤ 8
Ash, A	(%), dry	A2.0 ≤ 2,0	A5.0 ≤ 5,0	A7.0 ≤ 7,0
Mechanical durability, DU	(%), as received	DU97.5 ≥ 97.5	DU96.5 ≥ 96.5	DU95.0 ≥ 95.0
Fines, F	(%), as received	F1.0 ≤ 1,0	F2.0 ≤ 2,0	F2.0 ≤ 2,0
Additives	W(%) dry	≤10, Type and amount to be stated	Type and amount to be stated	Type and amount to be stated
Net calorific value, Q	MJ.kg^{-1}, dry	Q19, Q ≥ 19	Q19, Q ≥ 19	Q18, Q ≥ 18
Bulk density, BD	kg.m^{-3}, as received	BD650 ≥ 650	BD650 ≥ 650	BD650 ≥ 650

High quality pellets can be produced without an additional binder. Pelletizing after torrefaction requires specialist know-how of the densification of wood mass under high pressure. However, the pelletizing performance is strongly dependent on biomass feedstock and good control of the torrefaction conditions. Without an additional binder, the window for tuning the product quality to logistics and end-use requirements may be small (Kiel 2013).

The mechanical durability of the torrefiedpellets can be similar to traditional wood pellets, depending on the process circumstances and the raw materials. Wood also contains its own natural binder, which is called lignin and can be activated under high temperature. However, the wood’s own lignin is not always enough to produce good quality and sustainable pellets. Lignin acts as an important factor in the internal binding of the pellet. Lignin slightly degrades during the torrefaction process, depending on the conditions of process. Manufacturing of the torrefied pellets will require optimization of both the torrefaction and pelletizing processes, when temperatures are increased and high pressures are exerted. Many companies in the field of torrefaction technology are considered to use binders, such as lignin, glycerine, paraffin, molasses, bio-plastics and condensable fractions of torrefaction gas. An injection of water mist prior to the pelletizing process also seems to improve the binding characteristics of the torrefied material. The use of water is subject to intensive research these days (Koppejan et al. 2012).

Finland's most important tree species are Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), as regards to softwoods, and downy birch (*Betula pubescens*) and silver birch (*Betula pendula*), as regards to hardwoods. Most of a tree trunk is comprised of dead woody tissues and they only serve to support the weight of the crown. The actual building materials of wood are cellulose, hemicelluloses and lignin (Vanninen 2009).

A normal wood is typically comprised of 40 – 50% cellulose of the dry weight. Softwood contain less (25 - 30 w-%) hemicelluloses than hardwood (37- 40 w-%). Lignin is often called the cementing agent that binds the individual cells together and gives the mechanical strength. It is known that the lignin content is higher in softwood (27- 30 w-%) than in hardwood (20-25 w-%). Lignin largely consists of carbon, oxygen and hydrogen, which are elements of heat generation. In addition to the main building materials, wood also includes extract substances (<5 w-%), such as phenols, lipids, and terpenes (Alakangas 2000, McKendry 2002).

In this study, torrefied pellets were manufactured in a pilot plant, which was established by the company Torrec Ltd. located in Eastern Finland (Torrec Ltd. 2016). The pellet plant began pilot operations since August 2014. This one tonne-scale pilot plant of torrefied pellet offered the possibility to run a practical test, based on local biomass resources, for the first time in Finland. So far, the examinations have been based on small-scale laboratory tests or imported material batches from abroad. The pilot plant was a key factor in order to plot the properties of the raw wood materials and torrefied pellets. In addition, the suitability of the pellets to parallel firing in a coal plant was an encouraging issue for the establishing of the pilot plant. Because of this, the technologies and process control were possible to test in the pilot plant before launching the large-scale unit. Torrefaction technology has not yet been commercialized in a large-scale. The results will be very important for Finland, as there are plans to set up a commercial-scale (200 000 tonnes/year) bio-coal production plant in Eastern Finland (Nurminen 2012). Prospective Finnish customers are regional combined heat and power (CHP) plants who mean to replace a certain share of fossil coal with bio-coal pellets. The potential bio-coal market in Finland could be about 7 TWh or 1.2 million tonnes of pellets per year (Ranta et al. 2016).

The main purpose of this paper was to analyse the properties of torrefied pellets manufactured from different raw wood materials and in different conditions. All of the pellets were produced without an additional binder in the pilot runs, which was the main theme of this paper. The pelletizing process only used condensation water, which came through the torrefaction process. The qualities of the manufactured pellets were compared, when they were produced from different raw wood materials, and the temperature and the retention time were varied, regarding the driving parameters. In this case, the quality factors of the pellets meant the bulk density, moisture content, ash content, pellet length and diameter, mechanical durability, calorific values, and energy density per volume. In addition, some other quality factors, such as the particle-size distribution, were analysed from the beginning by using moist woodchips. Other purpose of this paper was to obtain accurate quality information on torrefiedpellets and its raw materials. This paper highlights the novelty of the present process and its profitability for the bio-fuel industry in general and specifically for the pellet producers.

MATERIAL AND METHODS

Material

The production plant of the study solely used wood chips as a raw material, which was suitable for the torrefaction process. Six different wood chip materials were used in the study. The wood materials used in the pilot runs were obtained from hardwood species as birch and softwoods as spruce and pine. These wood chips were made of pulp-wood-sized trees felled in March, two months before the pilot runs. The fourth lot of mixed hardwood chips were imported from Russia, and consisted mainly of hardwood species, such as birch and aspen. Also, birch veneer chips and spruce veneer chips from a plywood plant were tested. The particle-size of those veneer chips was slightly higher than the previous wood chip materials and they did not contain any other bark, like woodchips.

It was found that a large share, F20 – F25, of fine fraction (<3.15mm) caused problems for the torrefaction process at the beginning of the pilot runs. Fine fraction caused a varying of the quality of the pellets and, therefore, the calorific values and other values may remain low. The reason for a high share of fine fraction might be the blunt edges of a mobile chipper. A decision was made to screen the pulp-woodchip material from fine fraction, which helped to improve the quality of the pellets before the pilot runs. The mobile screening with Keestrack Combo (Keestrack Croup 2016) was a key factor in obtaining a good quality pellet in a pilot plant of this size. Also, other woodchip materials were screened before deliveries from the starting point to the pilot plant.

All of the torrefied pellets were done without any additional binder, like a tall oil, which ensures an additional advantage, as many previous challenges (Kiel 2013) were reported concerning the torrefied pellets quality without a binder. The pelletizing process always requires some moistening liquid to facilitate the producing of pellets. The pelletizing process now utilised condensation water obtained from the torrefaction process.

Methods

Pilot plant

The pilot plant for torrefaction technology was constructed by the company Torrec Ltd. The plant was located in Mikkeli, Eastern Finland and started operations since August 2014. This pilot site contains the entire process, including the drying, torrefaction, and pelletizing. The effective capacity was 2,200 tonnes per year. In practice, the units produce tonnes cale batches, allowing representative logistics and end-use performance testing by industry, and the actual capacity was lower. The entire pilot plant was a batch principled production plant. Normally, about 9 – 10 m^3 (bulk) of woodchips (approx. >300 $kg\cdot m^{-3}$) were input into the process, resulting about 1.5 – 2.0 tonnes of torrefied pellets. This pellet amount was always similar to the pilot plant runs in this study. The technology of torrefaction was based on a vertical reactor. In the process, woodchips flow due to the influence of gravity without drives or actuators. Torrefaction occurs through steam conduction to a steam radiator and by exact process control. The torrefaction process received its heating power from steam, which was directly conveyed from the regional CHP plant, which was located next to the pilot plant.

Process

At the beginning of the process, woodchips are moved from a raw material pit to the torrefaction unit via a screw conveyor (Fig. 1). The phases of the torrefaction process take place in the torrefaction unit: pre-drying, post-drying, torrefaction, and the cooling of solids. The pre-drying stage was carried out between 100°C and 200°C, therefore, there was no need for separate drying unit in the process. The pre-drying stage was performed for woodchips in order to remove the free water (above 30%) from the wood. Thereafter, the main torrefaction stage was performed between 240°C and 260°C. The time for the torrefaction stage varied normally between 1.5 – 2.0 hours. Due to the high torrefaction temperatures, the pulling out of wood from the torrefaction unit required a cooling of the wood before pelletizing. There was a storage silo between the torrefaction and pelletizing unit, where in the final cooling takes place.

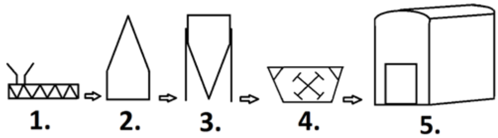

Fig. 1: The process sketch: screw conveyor (1.), torrefaction unit (2.), storage silo (3.), hammer mill (4.) and pelletizing hall (5.).

The torrefied wood mass was conveyed to the hammer mill, wherein the wood was crushed after the torrefaction process. The hammer mill had a 5 mm of screen mesh, but a part of the fraction was of a very small particle size, due to torrefaction. Finally, the crushed wood mass was conveyed to the pelletizing hall (Fig. 2). The crushed wood was slightly moistened with condensation water obtained from the torrefaction process before pelletizing. The used amount of water in one pilot run varied between 100 – 150 litres, depending on the success of the pelletizing. The purpose of moistening was to reduce the friction in the pelletizing process and to bind the material. A pellet squeezer was Munch RMP 650 and its capacity was 220 kW. The squeezer always operated at full power and the used amps were twice 145 – 165A. The crushed wood mass was pushed through a perforated iron matrix (Fig. 3). The essential part of the matrix was the 65 mm length compression channel, into which the wood mass was fed continuously more during the pelletizing. After pelletizing the pellets was screened of most of the fine particles and packed into large flexible bags (1 m^3), which had been made of polyethylene.

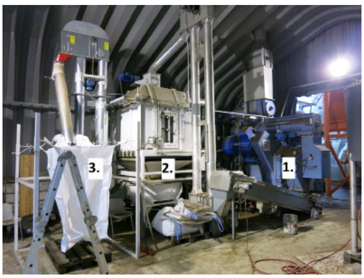

Fig. 2: The pelletizing hall, wherein were the pelletizing unit (1.), screening unit (2.) and bagging unit (3.).

Fig. 3: Iron matrix, which was used in the pelletizing process.

The torrefaction reactor was airproof during the process, in which case there were anoxic conditions. On the other hand, hatches can be opened for maintenance purposes. The water vapour was used to achieve the anoxic conditions in the heating process with the intention of replacing the oxygen. In addition, the torrefied wood material cools to the low temperature of approx. 100°C, by water vapour after torrefaction. After this process, the torrefiedwood material was moved to the crushing and pelletizing process. The pelletizing phase contains flammability and explosion risks, when the water vapour is also put into operation. The water vapour also prevents the dusting of the wood. All processes received their motion power from electricity. The next step of this technology is a commercial scale, in which the process will be continuous. The entire process is then built of separate drying and torrefaction units.

Pilotplant runs and schedule

All of the pilot plant runs were carried out during May and June 2015 and only the mixed hardwood chips lot imported from Russia was carried out during November 2014 of the previous year. The final laboratory analysis was finished in July 2015. All of the important process times and temperatures are presented in the Tab. 3. Peng et al. (2013) reported in their own study that a suitable torrefaction condition is a temperature of 250 to 300°C, with a mass loss of about 30%.

Tab. 3: Torrefaction process times and temperatures.

Woodchip material	Total time (h:min)	Max. temperature of reactor (°C)	Max. temperature of biomass bed (°C)
Mixed hardwood	1:36	254	247
Birch	1:36	259	250
Spruce	2:08	249	240
Pine	1:42	259	252
Spruce veneer	1:51	255	246
Birch veneer	2:13	257	250

It can be said that the torrefaction process was always started from a temperature of 160°C during the pilot runs. The torrefaction time was, in practice, the time interval, when a steam valve was fully opened and closed. A length of less than two torrefaction hours were carried out on two separate runs and these higher times called for three runs. The length of each run was approx. 40 – 50 minutes. The maximum temperature of the reactor was measured with a temperature sensor, which was located between the steam radiator and the chips mattress. The maximum temperature of the biomass bed was measured on the upper surface of the bed.

Sampling and laboratory tests

Sampling was performed in the same manner for both moist woodchips and final pellets. Sampling followed the general standards: SFS-EN 14778: en (2012) and SFS-EN 14780:en (2012). Every sample was taken and placed in a lidded bucket from each batch during the pilot runs. All of the buckets were stored in a cold room at 5°C before the laboratory tests.

The particle size distribution, bulk density, MC, ash content, length and diameter of pellets, mechanical durability of pellets, calorific values, and energy density per volume were tested from each sample material within the laboratory. However, not all of the above mentioned analyses were performed for the test materials, depending on the suitability of the material and the test.

The test materials were analysed, according to the following standards of solid bio-fuels: SFS-EN ISO 17827-1:en (2015), SFS-EN ISO 17828:en (2015), SFS-EN ISO 17829:en (2015), SFS-EN ISO 17831-1:en (2015), SFS-EN ISO 18134-1:en (2015),SFS-EN ISO 18122:en (2015).

The calorific values (SFS-EN ISO 1716: en 2011) and energy density per volume (Alakangas 2014b) were estimated values.

RESULTS

Woodchips

The share of fine fraction was rather high with the pulpwood chips at F20 – F25 before mobile screening. After screening, the fine fraction dropped to F5 – F10 (Tab. 4). The share of fine fraction was also small in other pre-screened woodchip materials at F5 – F15. The main fraction was classed in P16 for all woodchip materials, when the main fraction was $3.15 < P \leq 16$.

Tab. 4: Particle size distribution of woodchips.

Woodchip material	Fine fraction	Main fraction	Coarse fraction	Median of distribution (mm)	Longest piece (mm)
Mixed hardwood	F15	P16	-	5.3	80
Birch	F10	P16	-	6.3	70
Spruce	F5	P16	P16	7.1	60
Pine	F10	P16	-	5.5	80
Spruce veneer	F5	P16	P16	7.6	220
Birch veneer	F5	P16	P16	10.3	210

The quality results of woodchips are presented in the Tab. 5. The woodchips would have now been too old to be analysed after the entire pilot runs. The enclosed Tab. 5 shows that the MC was high, especially for coniferous tree species. The ash content was low for spruce veneer and birch veneer chips, because they did not contain any bark. The energy content (Qnet, d), as a dry basis of both birch species, was the highest.

Tab. 5: Quality results of woodchips.

Woodchip material	Moisture content (w-%)	Bulk density (kg.m^{-3})	Ash content (w-%)	LHVa Qnet,d (MJ.kg^{-1})	Qnet, ar^{b} (MJ.kg^{-1})	Ear (MWh.m^{-3}) (bulk)
Mixed hardwood						
Birch	42.7	312	1.53	19.84	10.33	0.89
Spruce	51.3	310	1.79	18.77	7.89	0.68
Pine	60.5	371	1.37	18.54	5.84	0.60
Spruce veneer	57.4	348	0.29	18.87	6.65	0.64
Birch veneer	45.9	322	0.45	18.91	9.10	0.81

[a]Lower heating value (low)

[b]Net calorific value as received, contains moisture

Torrefiedpellets

The measurement results of the pellet length, diameter, and share of fine fraction and mechanical durability are presented in the Tab. 6. Tab. 6 shows that the average length of hardwood pellets, as mixed hardwood and both birches was the largest. The screen of the pellet unit had a diameter of 8 mm, so all the pellets were close to that value. Pellets made of pine woodchips and spruce veneer chips had the largest share of fine fractions, at more than 0.8 w-%. Also, the mechanical durability of these pellets was the poorest, less than 92.6 w-%. Rudolfsson et al. (2015) indicated that the process window to optimize the pellet strength was narrow and, surprisingly, somewhat higher MC at higher degrees of torrefaction increased the strength of crush of the pellets. On the other hand, Shang et al. (2013) reported that a negative influence was found for the pellet strength when the MC was beyond 5%. The pellets are shown in the Fig. 4.

Tab. 6: Results of pellet length, diameter, and the share of fine fraction and mechanical durability.

Woodchips material	Length (mm)	Diameter (mm)	Fine fraction (w-%)	Mechanical durability (w-%)
Mixed hardwood	17.06	7.99	0.16	96.6
Birch	10.79	7.95	0.57	97.4
Spruce	10.33	7.99	0.10	96.8
Pine	9.07	7.93	0.85	91.8
Spruce veneer	7.97	7.99	0.81	92.6
Birch veneer	13.11	8.08	0.24	96.8

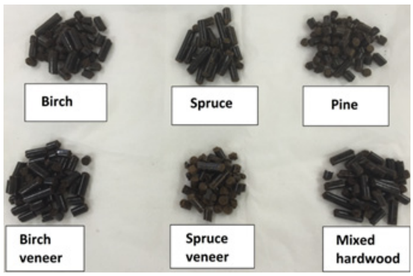

Fig. 4: The pellets which were made of different wood species.

The quality results of torrefied pellets are presented in the Tab. 7. The enclosed table shows that the MC of pellets varied between 4.4 – 8.6 %. The bulk density of all pellets was close to 700 kg.m^{-3}. Spruce veneer had the lowest bulk density 649 kg.m^{-3}.

In the case of pellets and also woodchip materials, the ash content was low for spruce and birch veneer chips, because they did not contain any bark. The energy content as a dry basis (Qnet, d) was the highest for spruce veneer, but the highest MC (8.60 w-%) decreased some its energy content as received (Qnet, ar). The energy content as received was the highest for spruce and birch veneers. However, the low bulk density decreased the spruce veneer towards the worst, as regards the energy density (Ear). Mixed hardwood and birch veneer had the highest energy densities, more than 3.6 MWh.m^{-3} (bulk).

Tab. 7: Quality results of torrefied pellets.

Woodchip material	Moisture content (w-%)	Bulk density (kg.m^{-3})	Ash content (w-%)	LHVa Qnet,d (MJ.kg^{-1})	Qnet,ar^{b} (MJ.kg^{-1})	Ear (MWh.m^{-3}) (bulk)
Mixed hardwood	6.57	704	1.31	19.91	18.44	3.61
Birch	6.40	678	1.23	19.37	17.96	3.38
Spruce	4.40	699	1.43	18.47	17.53	3.40
Pine	6.80	682	1.30	19.96	18.43	3.49
Spruce veneer	8.60	649	0.87	20.53	18.56	3.34
Birch veneer	4.98	699	1.16	19.88	18.77	3.64

[a]Lower heating value (low)

[b]Net heating value as received, contains moisture

DISCUSSION

The whole plant was a batch principled production plant and it solely used woodchips as a raw material or feedstock. The pilot project runs were performed with various raw wood materials and some altered driving parameters in the study. After each test run, quality factors were defined from woodchips of beginning and final products.

The studies of the previous years (Wolfgang 2012, Kiel 2013) have proven a higher energy content of torrefied pellets than in the analyse results of these pilot project runs. Kiel (2013) has reported a MC of 1 – 5% and energy content as received of 18 – 24 MJ kg·m^{-3}. In this study, the respective values were 4.4 – 8.6% and 17.5 – 18.8 MJ kg·m^{-3}. The main torrefaction stage was performed between 240°C and 260°C. That temperature range was perhaps too low to manufacture pellets, in which would have extremely high energy content. The delivered steam from the near-site biomass CHP-plant defined the maximum torrefaction temperature. An additional reason for the lower energy content of pellets may have been the moistening of pellets with condensation water during the pelletizing process.

The raw material chips had energy content as received from 5.8 to 10.3 kg·m^{-3} at the beginning of the torrefaction process, so the energy content of pellets had obtained a huge improvement. All woodchip materials were classed in the P16 category, as regards the main fraction. The share of fine fraction was small in woodchip materials at F5 – F15 after the separate screening. The small share of fine fraction was an important issue in the production of top quality pellets in this pilot plant. Otherwise, the fine fraction can form obstructions to the chips mattress and cause a varying quality of pellets. The quality issue will not be a problem in a continuously operating plant, where all the entire fine fraction will be burned during the process.

The average length of hardwood pellets as mixed hardwood and birch veneer was the largest. Also, these pellets had the highest bulk and energy densities at more than 3.6 MWh·m^{-3} (bulk). The energy density is the main numerical value, which best describes the energy quality of pellets. So, it can be concluded that hardwood was the best raw wood material to produce torrefied pellets at this pilot plant. In addition, the experiences of pelletizing process indicated that hardwood material pelletized better than softwood material. All torrefied pellets were done without any additional binder, like a tall oil, which ensures the special advantage of avoiding the additional costs of a binder in the future. Condensation water obtained from the torrefaction process was the only binder in the pelletizing process. So, basically, the pilot plant was a closed circulation system.

Based on the study, the pelletizing process will not need an additional binder in the future. Only the mechanical durability of pellets made from softwoods was low, less than 92.6 w-%, in which case the pellets fail to reach the minimum requirement (≥95 w-%) of the prospective EN ISO 17225-8 standard (Alakangas 2014a). It would be necessary to use an additional binder to manufacture durable torrefiedpellets from softwood. Otherwise, all the quality requirements regarding the above-mentioned standard were achieved under all woodchip materials. If there is a need to use the additional binders, then sawdust could be a brilliant raw material as a binder. Peng et al. (2015) indicated, that since raw sawdust is abundantly available and much cheaper than lignin and starch, it is recommended as a low-cost and effective binder.

CONCLUSIONS

The manufacture of torrefiedpellets without an additional binder should be tested more in order to learn new aspects about the difficulty of pelletizing and the durability of pellets in the long term. Normally, as the temperatures of reactor are increased, the quality of pellet may then weaken. When considering test runs in the future, the small-scale laboratory runs with a small reactor could be somewhat suitable for testing the benefit of the manufacture of torrefied pellets without a binder. By this procedure, the study would achieve both various test repetitions and be more dependable. The weakness of this study was the repeatability of pilot runs, which was difficult to realize. The arrangements for the pilot project runs were difficult to implement, time-consuming and costly. Additionally, it would have been useful to carry out pilot production runs at higher process temperatures. The maximum temperature was now only 260°C, due to the steam of the CHP-plant.

The pilot plant was the key to achieve experiential knowledge from torrefaction and pelletizing processes. In addition, the small problems that occurred in the process during the pilot runs can be solved, when the next step towards the continuously operating plant is taken. This step will be the next move, whilst the correct formulas for producing a top quality pellet are now known better. The best energy quality pellet will be formed when the woodchips are torrefied at close to 280°C at first. Then, the consisting pellet will receive high energy content as received, as well as a low MC. In addition, the pellet requires a high bulk density, when it has a high energy density. Of course, the torrefied pellet must be produced from a raw wood material, such as hardwood.

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