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Integration of SRF and carbonization plant for small forestry farms

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Abstract

A continuous oxidative carbonization pilot unit, with a capacity of 50 kg/h, has been developed and built by RE-CORD; reported performance data shows that the unit can produce high quality charcoal, suitable for BBQ, metallurgy of activated-carbon manufacturing, as well as biochar. Charcoal yield in excess of 24 wt% (dry) has been achieved, with a fixed carbon content higher than 85 wt% (dry). In this work, the up-scaled 250 kg/h demo plant has been designed, and the construction, operation and maintenance costs estimated. It was assumed to feed the plant with a dedicated SRF of either poplar or robinia, which represents a very innovative and yet unexplored value chain.
Performance data are reported along with economic evaluation of the whole chain. Results shows how a land management scheme based on SRF coupled to innovative small-scale biomass carbonization technology represents an appealing opportunity for business diversification in small and medium forestry enterprises.

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Keywords: charcoal, biomass carbonization, oxidative pyrolysis

1. Introduction

Short rotation forestry (SRF) consists of planting a site and then felling the trees when they have reached a size of typically 10-20 cm diameter at breast height. Depending on tree species this usually takes between 8 and 20 years, and is therefore intermediate in timescale between short rotation coppice and conventional forestry [1].

Charcoal is a multifaceted products with a surprisingly large number of properties and applications: in developing countries it is mainly used as domestic fuel for cooking and heating [2], but it is also an important

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industrial feedstock in metallurgy, because relative to fossil fuels, charcoal contains virtually no sulfur or mercury and very little nitrogen and ash [3], and also due to its high reactivity and porous structure. Though reliable estimates of charcoal production volume on a global scale are missing, FAO, with data gathered from official, semi-official, estimated and calculated figures, reported that in 2014 the worldwide production of charcoal exceeded $53 \cdot 10^6$ ton [4]. Charcoal can also be used as biochar, increasing the carbon content of the soil and thus allowing carbon negative actions.

Biomass carbonization is the process of converting solid, lignocellulosic biomass into charcoal; it is currently operated at several scales, encompassing manual, rudimental batch methods and industrial, continuous systems, with reported throughput up to several tens of thousands ton per year. Reported yields range from 8-12% for traditional kilns, 12-17% for brick kilns, 14-20% for standard industrial facilities and 25-33% for advanced industrial processes [2]. A major concern with charcoal production facilities is related to volatiles released in the atmosphere: while larger plant operates either a post-combustion of the volatiles or recovers the organic compounds that are being produced, smaller and more rudimentary systems directly vent the off-gases, generating plenty of harmful emissions, e.g. product of incomplete combustion, and greenhouse gases [5]. Along with improper post-harvest land and forest management [6], these emissions represents the main environmental impact of charcoal manufacturing in traditional systems.

Since 2013 RE-CORD has been developing an innovative biomass carbonization process (CarbOn, patent pending) and is currently operating the first pilot plant, rated for a capacity of 50 kg/h (feed), based on its proprietary layout. CarbOn operates on the autothermal process principle, i.e. heat for the process is internally provided by combusting part of the feedstock and evolved volatiles inside the reactor, the so called *oxidative pyrolysis*. This allows for process intensification in biomass pyrolysis. A first test campaign has been conducted between 2014 and 2015 [7]. The results from the experimental campaign on the CarbOn pilot supported the design of a larger demo unit.

Backed by the aforementioned performance data collected during the operation of CarbOn pilot unit, the present work reports the technical viability and economic profitability of coupling SRF and the demo carbonization plant, sized at a scale that can properly match the size of an average forestry company operating in central Italy (250 kg/h feed).

2. Materials and methods

2.1. Feedstock

Carbonization tests in the pilot plant have been carried out on mixed wood chips, provided by a local forestry company (PINOSA, Italy); The biomass used was a mixture of a different chipped hardwoods (acacia, alder, ash and elm). Prior to the test, the material was left aground to dry out below 20 %wt moisture content.

2.2. Pilot carbonization plant (CarbOn)

The CarbOn pilot plant is a continuous biomass carbonization system based on open top, downdraft technology, operating in oxidative pyrolysis. The pilot is essentially composed by three sections, detailed in Fig. 1: (1) loading and conversion of biomass; (2) charcoal discharge and cooling system; (3) extraction and burning of the pyrolysis vapors. The plant, made in stainless steel (AISI 304 and 316) and supported on a self-standing 6x2.5m structure, is rated for 50 kg/h of biomass with up to 20 wt% moisture content.

Section 1 comprises the gate valve, kept wide-open in normal operation, and the reactor body. The gate valve, non-hermetic, is placed on top of the reactor and ensures the entry of biomass and oxidant (air). The reactor is externally insulated and consists of a cylindrical volume. Here, biomass is converted in a controlled oxidative environment in the temperature range of 500-750°C with a solid residence time of approx. 3 h in the reactor and 2 h in the cooled discharge. By operating in open-top mode, the plant is intrinsically explosion-proof, as it cannot go in overpressure in case of fault.

Section 2 comprises a screw conveyor and air-tight tanks for the collection of charcoal. The screw conveyor is water cooled, allowing a safe discharge of the solid in the air-tight collection tank.

Section 3 comprises a cyclone for dust abatement, an air-blown ejector and a torch. Hot vapors are extracted from the bottom of the reactor by the ejector, capable of working with good reliability up to 600°C, and with tar-loaded condensable vapors. It is important to note that the piping system must be kept at temperatures above 380°C to avoid tar condensation and thus consequent possible clogging of the line.

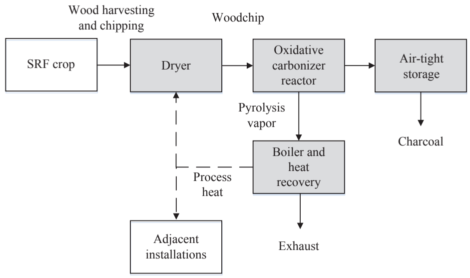

Fig. 1. CarbOn pilot unit (left) and SRF-Carbon demo unit coupling scheme (right)

2.3. Analytical methods and instrumentation

Chemical and physical analyses on solid and gas were performed at RE-CORD analytical laboratory according to international standard and internal methods and each determination was carried out at least in triplicate. Reference to appropriate standard is reported next to each measurement in Table 1.

2.4. Plant performance data

Key performance data of the pilot unit have been calculated from the properties of biomass and charcoal produced in the test carried out on November 3, 2016. The carbonization process has been characterized in terms of four different parameters: charcoal yield (eq. 1), fixed carbon yield (eq. 2), char carbon yield (eq. 3), net energy conversion efficiency (q. 4), according to the following formulations:

$$Cy = m_{char}/m_{bio} \tag{1}$$
$$fCy = Cy \cdot [\%fC/(100 - \%feed\ ash))] \tag{2}$$
$$CCy = Cy \cdot (\%C_{char}/\%C_{bio}) \tag{3}$$
$$\varepsilon = (m_{char,ar} \cdot LHV_{char,ar})/(m_{bio,ar} \cdot LHV_{bio,ar}) \tag{4}$$

Charcoal yield (*Cy*, eq. 1), is a measure of efficiency of the pyrolysis process, where m_{char} and m_{bio} are the dry mass of charcoal and biomass respectively. **The fixed-carbon yield** (*fCy*, eq. 2), proposed by Antal and co-workers [8], measures the effective conversion of the ash-free organic matter in the feedstock to a relatively pure, ash-free carbon, where % feed ash is the percentage ash content of the feed. **Char carbon yield** (*CCy*, eq. 3), proposed by Antal and co-workers [3], is a measure of the elemental carbon of feed that is retained in the charcoal, and is particularly significant for carbon sequestration purposes. For eq. 3, $\%C_{char}$

and $\%C_{bio}$ are the elemental carbon content of dry charcoal and biomass respectively. Finally, the **net energy conversion efficiency** (ε, eq. 4) represents the fraction of biomass chemical energy retained by charcoal, and $m_{char,ar}$ and $m_{bio,ar}$ are respectively the as-received mass of charcoal and biomass, and LHV is the lower heating value.

2.5. Performance and cost estimate of the carbonization demo unit (250 kg/h)

As a conservative hypothesis, it was assumed that the demo plant attains the same performance of the pilot unit, in term of all the four yields defined in section 2.4, thus neglecting the beneficial scale effect. While the pilot unit simply burn the off-gases, the up-scaled demo plant entails some more refined features that enhance the energy recovery and mitigate the environmental impact of the system; therefore, the larger systems considered in this study includes a pyrogas burner, a heat recovery boiler and bag-house filter for exhaust de-dusting before stack and all the heat generated by the combustion of the pyrogas is fed to an external process. Net boiler efficiency (overall) was assumed equal to 90%.

A cost estimate of first-plant construction was drawn basing on the design constraint and operation scenario, and was supported by quotation of individual components from individual manufacturers. The estimate of operating expenditure was based on the use scenario of 5 days per week over three shift of 8 hours each; the heat recovered from the boiler was assumed to be sold at 6 €c/kWh, and the amount of available heat estimated after the internal consumption for biomass drying. The cost of labor was estimated at 12 €/h, cost of service calculated as 4% of capex, and cost of insurance 2% of capex; the carbonization plant operates automatically, and the workload has been considered to be 6 h per day.

Thermal energy required for drying biomass from 45 to 10 wt% (wb) was estimated at approx. 4MJ/kg_{dry} (1.1 kWh/kg_{dry}) [9]. Charcoal was assumed to be sold on the wholesale market at 0.65 €/kg.

2.6. SRF plot

SRF is the ideal forestry management scheme to be coupled with a carbonization plant as it provides consistent size of feedstock, after field processing and size reduction, which in turns reflects in a less dispersed charcoal particle size.

For calculation, the agronomic data reported by Coaola and Grignetti [10] on the productivity and specific cost per hectare of poplar and robinia cultivated at SRF scheme have been adopted. In their study 2514 hectares over 350 plots, cultivated by 255 farms, distributed across eleven distinct Italian regions, have been evaluated between 2008 and 2010. In the present study we retain the same land management scheme proposed by the Authors: a cut every two years and a plantation lifespan of 10 years, without plot irrigation. The biomass yield per hectare and corresponding production cost, in 2010 €, were estimated at 8.55 t_{dry}/ha/y and 68 €/t_{dry} for poplar and 8.1 t_{dry}/ha/y 58 €/t_{dry} for robinia.

3. Results and discussion

3.1. Charcoal quality and carbonization yields in pilot unit

Table 1 reports the results of the characterization of biomass the produced charcoal. While the feedstock is an ordinary lignocellulosic biomass, it can be noticed that the produced charcoal features some unique properties, i.e. very high fixed carbon (85 wt%) and elemental carbon content (88 wt%). The amount of fixed carbon is of prominent interest for metallurgical applications as it defines the grade of the material and is used to determine its cost. Except for the granulometry, which can be easily overcome by agglomeration to form charcoal briquette, the produced charcoal strictly complies with EN 1860-2, the European product standard for barbecue application.

Table 1. Analyses of woodchips and charcoal.

	Biomass	*Charcoal*	*Reference Norm*
Physical Characteristics			
Granulometry	P63	78 % > 16mm	EN 14961-1:2011 | EN 15149-1:2010
Bulk density (ar, kg/m^3)	228	156.1	EN 15103:2009 | internal
Proximate analysis			
Moisture (ar, wt%)	10.96	2.3	EN 14774-2:2009
Volatile matter (db, wt%)	80.75	12.1	EN 15148:2009
Ash (db, wt%)	0.75	3.0	EN 14775:2009 | EN 1860-2:2005
Fixed carbon (db, wt%)	18.5	85.0	-
Ultimate analysis			
C (db, wt%)	48.51	88.0	EN 15104:2011
H (db, wt%)	7.13	2.0	EN 15104:2011
N (db, wt%)	0.33	0.9	EN 15104:2011
O (db, wt%)	43.29	6.2	EN 15104:2011
Others			
LHV (db, MJ/kg)	18.73	32.2	EN 14918:2009
Surface area - granules (m^2/g)	-	94.7	ISO 9277
Surface area - powder (m^2/g)	-	106.6	

Considering the measured charcoal and biomass properties and mass yields achieved during test, it was possible to calculate the main performance parameters (Eq. 1-4); the attained average charcoal yield (Cy) was 24.0 wt% (db), the fixed carbon yield (fCy) 20 wt%, the char carbon yield (CCy) was 42.8 wt% and the net energy conversion efficiency (ε) of 40.2 % (wb). Volume concentration of permanent gases in the pyrolysis vapors were also measured before incineration; dry pyrolysis vapor was composed of: CO2 17.4%; CO 13.3%; H2 17.8%; N2 46.3%; CH_4+ 5.2% (including C_2H_4 and C_2H_6).

3.2. Demo plant performance

Considering the demo plant, with a capacity of 250 kg/h of biomass at 15 wt% moisture content, and assuming to attain the same performance of the pilot, a production cycle of 5760 h/y (24 h a day for 5 days a week for 11 months), each unit will manufacture around 294 ton of high quality charcoal and generate around $8.4 \cdot 10^3$ GJ of heat per year (either as steam or hot water); part of the heat will be used internally to dry the harvested wood chips, therefore the net heat available for the market is $3.5 \cdot 10^3$ GJ per year.

3.3. Land requirement for SRF plot

Considering that 90% of the harvested biomass can be used to feed the carbonization plant, the rest being leafs, branches and dust, and basing on the agronomic plot-yield data reported in section 2.6, the extent of land required for the SRF plantation can be assessed between 159 ha and 168 ha, for poplar and robinia respectively.

3.4. Economic scenario

In a virtuous land management scenario, the carbonization plant of 250 kg/h has been coupled with a SRF crop to enhance viability and profitability of carbonization adoption among small and medium scale forestry industries. Investment cost (CAPEX) was estimated in 450 k€. Woodchip production via SRF was the predominant - among the others - cost component, and worth 92 k€/y for poplar and 79 k€/y for robinia, and the total annual costs, were respectively 137 k€/y and 123 k€/y. Revenue from charcoal selling on the gross market was 191 k€ and from heat selling was 58 k€/y, for a total revenue of 249 k€. Total annual value of production and payback time were respectively 94 k€ and 4.8 y for poplar and, 108 k€ and 4.2 y for robinia.

4. Conclusions

During the experimental test, the CarbOn pilot unit (50 kg/h) produced a high quality charcoal with a high fixed carbon content. The manufactured charcoal can be used for various purposes, such as metallurgy, complies with the charcoal for BBQ product standard and therefore can be sold on the market for barbequing applications, and activated carbon manufacturing, but also biochar production for carbon sequestration can be considered as a viable product destination.

A scenario in which a SRF land management scheme is coupled to a larger demo carbonization unit (250 kg/h), charcoal is sold to the market and the produced heat is partly recovered for wood drying, and partly sold to nearby plant for process demand, has been evaluated; the whole system is profitable, with short payback time (approx. 4 years) and marginal risks.

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