THE BIOMASS PYROCYCLING™ PROCESS

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ABSTRACT

A pyrolysis technology using moderate vacuum pressure conditions and a temperature in the range of 450-500°C is described. The process can recycle a wide variety of solid wastes such as used tires, plastics, auto fluff and biomass residues to useful chemicals and fuel products. For this reason the process has been named Pyrocycling™. Under such operating conditions, the organic matter in the feedstock is preferably converted to pyrolysis oils at the expense of the solid and gaseous products. The Pyrocycling™ pilot plant reactor is characterized by high overall heat transfer coefficients which can be as high as 250 W m^{-2} K^{-1}, depending on the kind of material treated. A comparison is made between direct biomass combustion and combustion of the biomass Pyrocycling™ products in an integrated pyrolysis combined cycle system designed to achieve high conversion of biomass to electricity.

INTRODUCTION

A vacuum pyrolysis technology for the recycling of various industrial and municipal wastes such as used tires (1), petroleum sludges (2), electric cables (3), automobile shredder residues (4), MSW (5) and biomass residues (6) has been developed over the last decade by a private research corporation called Pyrovac Institute, in collaboration with researchers at Université Laval (Québec, Canada). The process usually operates under a moderate vacuum of approximately 20 kPa absolute and a thermal decomposition temperature of 450-500°C. The technology has been licensed by the Université Laval to Pyrovac Technologies Inc. for the North American territory and to Ecovac Pyrocycling Technologies Inc. for the rest of the world. The last two companies are owned in equal shares by a Canadian corporation called Pyrovac Group Inc. (Québec, Canada) and a Dutch corporation called Ecotechniek b.v. (Holland, The Netherlands).

Roy *et al*. (7) already showed in 1985 that the use of a moderate to low vacuum during pyrolysis reactions favors the production of specific chemicals originating from biomass. The working principle is that vacuum prevents the breaking down of the primary fragments formed during the thermal decomposition reactions due to the short residence time of the vapors in the reactor. Under such conditions, organics in the feedstocks are preferably converted to liquid products as opposed to solid and gaseous products. The vacuum pyrolysis process has the potential to recycle waste materials to useful products which is the reason why it has been named Pyrocycling^{TM}. Examples are available in the literature for the Pyrocycling^{TM} of used tires to high value chemicals such as *dl*-limonene (8) and pyrolytic carbon black (9, 10), phenolics originating from bark residues and primary sludges (6) and oils, metals and char obtained from auto fluff (4) to name a few.

This paper discusses for the first time the potential of the Pyrocycling^{TM} process when liquid, solid and gaseous fuel products derived from biomass are used in a power station for the production of electricity.

PYROCYCLING^{TM} PROCESS DESCRIPTION

A schematics of the Pyrocycling^{TM} process is illustrated in Figure 1 below.

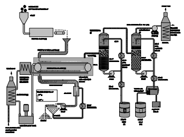

Figure 1
The *Pyrocycling*^{TM} Process

Once they have been pretreated *[1]*, the biomass residues are introduced under vacuum into the *Pyrocycler*^{TM}, a specially designed integrated equipment system *[2]*. The wastes are conveyed over horizontal plates *[3]* which are heated by a blend of molten salts which is maintained at a temperature of 500°C. This heat carrier is composed of a mixture of potassium nitrate, sodium nitrite and sodium nitrate and is primarily heated by means of a gas burner *[4]* which is supplied with the non-condensable gases produced by the process. An electrical induction heater *[5]* is optionally used to maintain a constant temperature inside the reactor. When heated, the organic matter in the feedstock is decomposed into vapors *[6]* which are rapidly removed from the reactor by means of a vacuum pump *[7]*. These vapors are then directed towards two packed towers *[8]* in which the heavy *[9]* and light oils *[10]* are recovered. The non-condensable gases *[11]* are directed to the burner *[4]* which heats the molten salts. The residual solid product is cooled at the reactor outlet.

The new reactor design described above includes a novel feedstock transport and agitation system for which an international patent has been claimed (11). This system produces a forced exchange between the feedstock particles heated at the surface of the heating plate and the colder particles located at the core of the bed of particles. Consequently, the heat transfer between the reactor and the pyrolyzed material is dramatically increased. The other novelty of this reactor is the indirect heating system involving commercial molten salts sold under the trademark of Hitec^{TM}. Overall heat coefficients ranging from 70 to 250 W m^{-2} K^{-1}, depending on the feedstock treated, are obtained with this new system combining the molten salts and the forced heat transfer mechanism (12).

BIOMASS PYROCYCLING^{TM} FOR ELECTRICITY PRODUCTION

Biomass conversion into oil and gas can be performed by thermochemical technologies such as vacuum pyrolysis, fast pyrolysis and gasification. The individual steps involved in the supply and conversion of woody biomass for energy have been outlined in detail for bioenergy systems such as combustion, fast pyrolysis and gasification (13). Several technico-economic assessments of biomass power generation technologies, including wood combustion, have been reported recently (14-16). Some of these feasibility studies include an examination of different pyrolysis processes (16). Little attention however has been paid in these studies to the energy content of the wood charcoal by-product. Furthermore, no work has been presented yet on the use of vacuum pyrolysis for power generation purposes.

In this paper, we propose to use the Pyrocycling^{TM} technology into an integrated scheme using a gas turbine and a steam turbine in a combined cycle to increase the electrical energy production per ton of wood. The process is called Integrated Pyrocycling^{TM} Combined Cycle (IPCC) in this paper. Such an approach can now be contemplated because of the new developments experienced by the gas turbine industry where the combustion of biomass-derived pyrolysis oils has been reported to be technically feasible (17). The question, addressed in this paper, is whether the energy required for the vacuum pyrolysis process would negate the gain in energy achieved through the use of the pyrolysis oils in an energy efficient combined cycle.

Typical yields of pyrolysis products obtained during the vacuum pyrolysis of biomass species such as spruce wood and fir and spruce bark residues are given in Table 1. The yield of pyrolysis oils is higher for wood at 47.4% than for bark at 34.9%. The total condensates which include the pyrolytic water represent a total of approximately 64% and 54% by weight of the pyrolytic products for softwood and softwood bark residues, respectively, on an anhydrous basis. The yield of wood charcoal ranges from 23.6% (wood) to 34.1% (bark) and the yield of non condensable gases, composed mainly of carbon monoxide, carbon dioxide and light hydrocarbons is almost identical at 11.5-12%. The values given for the bark residues experiment in Table 1 were obtained during a series of experiments (runs #H-33 and H-38 to H-40) where a few tons of biomass have been processed in a pilot plant reactor (75 kg/h throughput capacity). The pyrolysis of spruce wood was conducted batchwise in a 15 L reactor (run # G-66).

Table 1
Typical Yields (wt. %, anhydrous basis)

	Spruce Wood #G-66	Fir/Spruce Bark Residues #H-33
Pyrolysis oils	47.4	34.9
Pyrolytic water	17.0	19.5
Condensates	64.4	54.4
Wood charcoal	23.6	34.1
Gas	12.0	11.5
Total	100.0	100.0

Table 2
Gross Calorific Value of the Pyrolysis Products (MJ/kg, as-received basis)

	Spruce Wood	Fir/Spruce Bark Residues
Pyrolysis Oils	24.4*	342.2**
Wood Charcoal	26.7	30.4***
Gas	9.1	6.7

Moisture content: *5.5%; **1.4%; ***4.3%

Table 2 gives the gross calorific values for each of the as-received pyrolysis products. The pyrolytic oil which contains small amounts of water, has a rather high calorific value ranging from 24.4 to 32.2 MJ/kg for the softwood and the bark biomass, respectively. As shown in Table 1, vacuum pyrolysis of biomass yields a significant quantity of charcoal and the latter has a high calorific value, 26.7 and 30.4 MJ/kg for spruce and fir/spruce bark, respectively; it therefore represents a valuable and important solid fuel product obtained from biomass.

These data indicate that upon pyrolysis a substantial portion of the biomass feedstock internal energy is recaptured in the form of a liquid fuel (pyrolysis oil) and a solid fuel (wood charcoal) whose heating values are greater than the calorific value of the feedstock materials, thanks to the fact that a substantial portion of the oxygen in the biomass is converted to water and carbon dioxide. For example, the high heating value of spruce wood on an anhydrous basis is 20.0 MJ/kg and that of the fir/spruce bark sample investigated in this study is 22.4 MJ/kg. This analysis however does not take into account the process energy to convert biomass to oils, charcoal and gas. The latter value has been calculated below for a Pyrocycling^{TM} plant fed with 8.6 t/h of biomass @ 15% moisture.

The bark residue-derived pyrolysis oil was analyzed (Table 3) with the objective to use this material as a liquid fuel in gas turbines. The biooil has a relatively high calorific value and a low sulfur content. Its kinematic viscosity of 157 cSt could be further reduced, if necessary, by enabling a higher proportion of the pyrolytic water or moisture to condense at an earlier stage during the process. Ash levels in biooils can be significantly reduced using filtering techniques during processing which in turn reduces the alkali metal content; the remaining alkali metal content needs to be addressed through improvements in fuel processing, reduction by fuel additives and minimization of component degradation by the use of advanced protective coatings (18).

Table 3
Fuel Properties of Fir/Spruce Bark-Derived Pyrolysis Oil

Fuel Property	Biomass Pyrocycling^{TM} Oil
Density, kg/m^3 @ 15°C	1076
Gross	

Gross calorific value, MJ/kg	32.2
Water content, wt.%	1.4
Kinematic viscosity, cSt @ 50°C	157
Flash point, °C	68
Ash, wt.%	0.14
V, ppm	<1
Na, ppm	<1
Ca, ppm	107
K, ppm	22
S, wt.%	<0.01
pH	3.0

The direct biomass combustion process involves a conventional power plant with a Rankine cycle using bark residues, a dryer and a boiler, a steam turbine and a condenser. The direct combustion of wood in a boiler has a process efficiency of only 26%, since a great deal of energy is lost in the stack and condenser. For a 200 t @ 15% moisture per day biomass combustion plant, the process generates a total of 11.8 MWe (see Table 4, Scenario A).

Table 4
Biomass Combustion vs. Biomass IPCC

Scenario A	Scenario B*	Scenario C*
Dryer	Dryer	Dryer
Bark residues @ 15% moisture 8640 kg/h, 19.0 MJ/kg Boiler electricity generation efficiency: 26%	Biooil @ 1.4% moisture 2560 kg/h, 32.2 MJ/kg Boiler electricity generation efficiency: 26%	Biooil @ 1.4% moisture 2380 kg/h, 32.2 MJ/kg Combined cycle electricity generation efficiency: 40%
11.8 MWe	5.9 MWe	8.5 MWe
	Wood charcoal 2500 kg/h, 30.4 MJ/kg Boiler electricity generation efficiency: 26%	Wood charcoal 2500 kg/h, 30.4 MJ/kg Boiler electricity generation efficiency: 26%
	5.5 MWe	5.5 MWe
	Pyrolysis gas 845 kg/h, 6.7 MJ/kg Boiler electricity generation efficiency: 26%	Pyrolysis gas (Internal use)
	0.4 MWe	
	Process energy requirement	Process energy requirement

	(3.1 MWe)	NIL
Total output 11.8 MWe	Total output 8.7 MWe	Total output 14.0 MWe

* The data shown do not take into account the small amount of energy required to achieve the biotreatment of the aqueous phase.

Scenario B in Table 4 involves a dryer, a biomass Pyrocycling™ unit, a steam turbine and one or more boilers. As expected, when each of the pyrolytic products are burned to provide energy using the standard Rankine cycle whose efficiency is only 26%, the Pyrocycling™ process is less attractive than direct wood combustion. Scenario B generates a total of 8.7 MWe of electricity, in comparison with 11.8 MWe generated by direct wood combustion for the same power plant throughput capacity.

Figure 2 represents the Integrated Pyrocycling™ Combined Cycle system. In this process, the biomass containing 50% moisture on a wet basis is dried in a direct contact type dryer using flue gases from the process. No additional thermal energy is required to dry the biomass material since plenty of thermal energy is available from the various process flue gases. The air-dry biomass is fed into one of the three Pyrocycling™ units where it is pyrolyzed at a design throughput capacity of 8.6 t/h, at a temperature of 500°C and a total pressure of 20 kPa. The wood charcoal produced is burned in a boiler which provides energy for a steam turbine which in turn generates 5.5 MWe. The wood charcoal cannot be used in a combined cycle and a lot of energy is lost at the boiler stack. The thermal efficiency for electrical generation purpose is 26%. The IPCC uses the flue gas from the charcoal boiler for biomass drying. The latter contributes to the overall process efficiency. The vapors formed during the vacuum pyrolysis of the biomass are rapidly withdrawn from the Pyrocycling™ unit by a vacuum pump and are condensed in two cooling, packed towers. The resulting pyrolytic oil is burned and the energy produced is directed towards a gas turbine which is connected to a steam generator. All this energy is converted in a 40% efficient combined cycle for the generation of 8.5 MWe of electricity while the excess energy is also used to provide heat to the dryer. The non condensable gases are burned to provide up to 50% of the energy required for the pyrolysis process. A small fraction of the wood oil is used to provide the remaining 50% of energy needed. The Pyrocycling™ process itself requires 3.1 MWe to convert the original biomass into pyrolytic products. All this thermal energy is available from the process products as described previously. The total electricity production with this scenario is 14.0 Mwe.

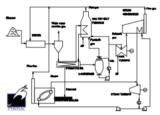

Figure 2
Schematics of the Biomass Integrated Pyrocycling^{TM} Combined Cycle

(IPCC) System

CONCLUSION

It has been determined that the pyrolysis under vacuum of biomass to pyrolysis oils, wood charcoal and gas followed by the combustion of the pyrolysis oils in a gas turbine combined cycle system, and the combustion of the wood charcoal in a boiler, steam turbine and condenser, is theoretically more thermally efficient to generate electricity than the direct combustion of wood in a conventional power plant with a Rankine cycle.

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