BIOMASS FAST PYROLYSIS

by

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Bioenergy is now accepted as having the potential to provide the major part of the projected renewable energy provisions of the future. Fast pyrolysis is one of the three main thermal routes, with gasification and combustion, to providing a useful and valuable biofuel. It is one of the most recent renewable energy processes to have been introduced and offers the advantages of a liquid product – bio-oil – that can be readily stored and transported, and used as a fuel, an energy carrier and a source of chemicals. Fast pyrolysis has now achieved commercial success for production of some chemicals, liquid fuel and electricity. Bio-oils have been successfully tested in engines, turbines and boilers, and have been upgraded to high quality hydrocarbon fuels although at a presently unacceptable energetic and financial cost. This review concentrates on the technology of pyrolysis and applications for the liquid product. The basic pyrolysis process and the characteristics of the main liquid product – bio-oil – are first summarised followed by a review of applications for bio-oil. The main technical and non-technical barriers to implementation are identified.
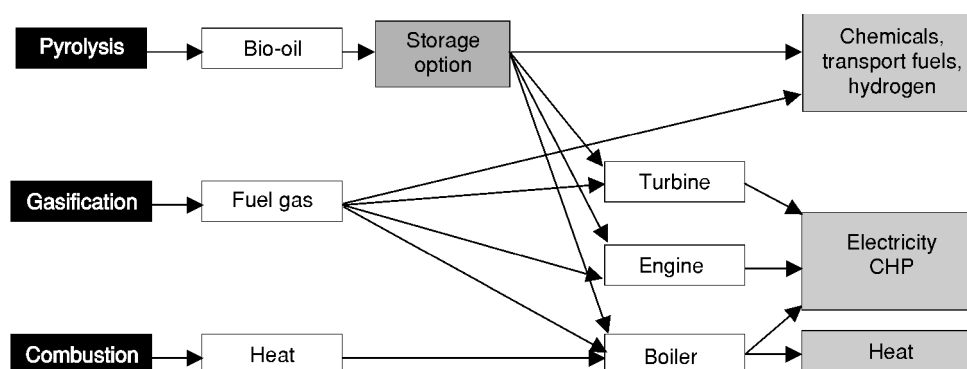
Introduction

Renewable energy is of growing importance in satisfying environmental concerns over fossil fuel usage. Wood and other forms of biomass including energy crops and agricultural and forestry wastes are some of the main renewable energy resources available. These can provide the only source of renewable liquid, gaseous and solid fuels. Biomass is considered the renewable energy source with the highest potential to contribute to the energy needs of modern society for both the developed and developing economies world-wide [1, 2]. Energy from biomass based on short rotation forestry and other energy crops can contribute significantly towards the objectives of the Kyoto Agreement in reducing the green house gases emissions and to the problems related to climate change [3].

Thermal conversion

Biomass fuels and residues can be converted to energy via thermal, biological and physical processes. In thermal conversion, combustion is already widely practised;

gasification attracts a high level of interest as it offers higher efficiencies compared to combustion; and fast pyrolysis is interesting as a liquid is produced that offers advantages in storage and transport and versatility in applications, although it is still at a relatively early stage of development. The products and applications of these thermal conversion processes are summarised in fig. 1.

Figure 1. Products from thermal biomass conversion

Combustion is widely practiced where-ever economically justified. The product can only satisfy the heat market directly or power production via a Rankine cycle or similar. Efficiencies are low at small capacities and fouling and emissions are problematic in many applications. Gasification offers higher efficiencies at all scales of operation, and while on the verge of being fully commercial still requires still requires demonstration at commercially attractive scales of operation. There are added incentives for production of liquid fuels and chemicals for example via methanol or Fischer Tropsch synthesis. Fast pyrolysis for liquids is the newest technology and least developed except for production of food flavours. It offers the advantage of a liquid that can be stored and/or transported to offer a more versatile optimised system. The bio-oil can also be used as an energy carrier and as a source of chemicals.

Pyrolysis

Pyrolysis is thermal decomposition occurring in the absence of oxygen. It is always also the first step in combustion and gasification processes where it is followed by total or partial oxidation of the primary products. Lower process temperature and longer vapour residence times favour the production of charcoal. High temperature and longer residence time increase the biomass conversion to gas and moderate temperature and short vapour residence time are optimum for producing liquids. Table 1 indicates the product distribution obtained from different modes of pyrolysis process. Fast pyrolysis for liquids production is of particular interest currently.

Table 1. Typical product yields (dry wood basis) obtained by different modes of pyrolysis of wood

Process	Conditions	Liquid	Char	Gas
Fast pyrolysis	Moderate temperature, short residence time particularly vapour	75%	12%	13%
Carbonisation	Low temperature, very long residence time	30%	35%	35%
Gasification	High temperature, long residence times	5%	10%	85%

Fast pyrolysis occurs in a time of few seconds or less. Therefore, not only chemical reaction kinetics but also heat and mass transfer processes, as well as phase transition phenomena, play important roles. The critical issue is to bring the reacting biomass particle to the optimum process temperature and minimize its exposure to the intermediate (lower) temperatures that favour formation of charcoal. One way this objective can be achieved is by using small particles, for example in the fluidised bed processes that are described later. Another possibility is to transfer heat very fast only to the particle surface that contacts the heat source. This second method is applied in ablative processes that are described later.

In order to illustrate the science and technology of thermal conversion in sufficient detail to appreciate the potential, fast pyrolysis is described at length.

Principles

In fast pyrolysis biomass decomposes to generate mostly vapours and aerosols and some charcoal. After cooling and condensation, a dark brown mobile liquid is formed which has a heating value about half that of conventional fuel oil. While it is related to the traditional pyrolysis processes for making charcoal, fast pyrolysis is an advanced process, with carefully controlled parameters to give high yields of liquid. The essential features of a fast pyrolysis process for producing liquids are:

- very high heating and heat transfer rates at the reaction interface, which usually requires a finely ground biomass feed,
- carefully controlled pyrolysis reaction temperature of around 500 ºC and vapour phase temperature of 400-450 ºC,
- short vapour residence times of typically less than 2 seconds, and
- rapid cooling of the pyrolysis vapours to give the bio-oil product.

The main product, bio-oil, is obtained in yields of up to 75% wt on dry feed basis, together with by-product char and gas which are used within the process so there are no waste streams other than flue gas and ash.

A fast pyrolysis process includes drying the feed to typically less than 10% water in order to minimise the water in the product liquid oil (although up to 15% can be ac-

ceptable), grinding the feed (to around 2 mm in the case of fluid bed reactors), to give sufficiently small particles to ensure rapid reaction, pyrolysis reaction, separation of solids (char), and collection of the liquid product (bio-oil).

Any form of biomass can be considered for fast pyrolysis. While most work has been carried out on wood due to its consistency, and comparability between tests, nearly 100 different biomass types have been tested by many laboratories ranging from agricultural wastes such as straw, olive pits and nut shells to energy crops such as miscanthus and sorghum and solid wastes such as sewage sludge and leather wastes.

Fast pyrolysis technologies

Since the oil crisis in the mid 1970s considerable effort has been directed toward development of processes for producing liquid fuels from lignocellulosic biomass. This led to the development of several fast pyrolysis technologies. Several reactor configurations have been shown to assure this condition and to achieve yields of liquid product as high as 70-80% based on the starting dry biomass weight [4]. They include bubbling fluid beds [5, 6], circulating and transported beds [7, 8], cyclonic reactors [9, 10], and ablative reactors [11].

In the 1990s several fast pyrolysis technologies reached near-commercial status. Six circulating fluidized bed plants have been constructed by Ensyn Technologies with the largest having a nominal capacity of 50 t/day operated for Red Arrow Products Co., Inc. in Wisconsin. DynaMotive (Vancouver, Canada) have demonstrated the bubbling fluidized bed process at 10 t/day of biomass and commissioned their first 100 t/day in July 2004 in Ontario. BTG (The Netherlands) operates a rotating cone reactor system at 5 t/day and is scaling the plant up to 50 t/day in the Far East. Fortum had a 12 t/day pilot plant operating in Finland until the end of 2003 [12]. ENEL retain their 15 t/day pilot plant in Bastardo which operates intermittently. The Wellman 6 t/d pilot plant still awaits commissioning.

The yields and properties of the generated liquid product, bio-oil, depend on the feedstock, the process type and conditions, and the product collection efficiency. Although biomass pyrolysis oils have been primarily expected to become alternative liquid fuels, other potential applications have also emerged and are reviewed in this paper.

Reactors

At the heart of a fast pyrolysis process is the reactor and most research and development has focused on the reactor. The rest of the process consists of biomass reception, storage and handling, biomass drying and grinding, product collection, storage and, when relevant, upgrading. A comprehensive survey of fast pyrolysis processes has been published that describes all the pyrolysis processes for liquids production that have been built and tested in the last 10-15 years [13] and this has been updated in more recent presentations [14, 15], so only recent developments are reported here.

Ablative pyrolysis

Ablative pyrolysis is fundamentally different from fluid bed processes from the mode of heat transfer through a molten layer at the hot reactor surface, use of large particles and absence of a fluidising gas. Recent developments include Aston University's (UK) development of their moving blade into a scalable system [16], and Pytec's pilot plant development at 50 kg/h which is being scaled to 12 t/day [17].

The Aston process is based on the previous reported work [11], but as this was limited to small scale applications due to the surface area controlled phenomena, which limited the plate size, a basic re-design was carried out and a high through system was designed, constructed and tested. This represented an small element of a pilot or demonstration reactor with a potential capacity of between 0.5 and 1 t/h and a scale up potential to 5 to 10 t/h. The vapour collection system is conventional with a quench column and electrostatic precipitator.

The Pytec process is bases on mechanical pressure of wood rods or planks onto a rotating heated plate in a sealed chamber [17]. The vapour collection system is conventional. A larger version is currently being constructed in north Germany and commissioning is planned for early 2005.

Screw pyrolysis

Forschungszentrum Karlsruhe (Germany) are developing a 10 kg/h fast twin screw flash pyrolysis reactor for production of bio-oil for gasification tests [18]. Few results are available from biomass tests. The objective is to produce a high yield of a transportable bio-oil – char slurry for subsequent large scale gasification [18].

Char removal

Char acts as a vapour cracking catalyst so rapid and effective separation from the pyrolysis product vapours is essential. Cyclones are the usual method of char removal however, some fines always pass through the cyclones and collect in the liquid product where they accelerate aging and exacerbate the instability problem.

Hot vapour filtration, analogous to hot gas filtration in gasification processes, gives a high quality char free product [19], however the liquid yield is reduced by about 10-20% due to the accumulation of char on the filter surface that cracks the vapours. The technique has been successfully developed by NREL and VTT.

A number of alternative approaches are being developed to overcome the problems associated with external hot vapour filtration – in-bed filtration and rotating particle separation. Twente University is studying the insertion of a hot vapour filter into the fluid bed, relying on the abrasion of sand in the fluid bed to keep the surface clean of char [20]. There are few results yet, but the char will still need to be removed from the fluid bed and substantial removal of gas from the fluid bed through the in-bed filter will significantly

affect the hydrodynamics of the reactor. TNO has developed a rotary particle separator within the pyrolysis reactor to enhance char separation [21].

Pressure filtration of the liquid is very difficult due to the complex interaction of the char and pyrolytic lignin, which appears to form a gel-like phase that rapidly blocks the filter. Modification of the liquid micro-structure by addition of solvents such as methanol or ethanol that solubilise the less soluble constituents will improve this problem and also contribute to improvements in liquid stability as described below.

Liquid collection

The gaseous products from fast pyrolysis consist of aerosols, true vapours and non-condensable gases. These require rapid cooling to minimise secondary reactions and to condense the true vapours, while the aerosols require coalescence or agglomeration. Simple heat exchange can cause preferential deposition of lignin derived components leading to liquid fractionation and eventually blockage. Quenching in product oil or in an immiscible hydrocarbon solvent is widely practised. Orthodox aerosol capture devices such as demisters and other commonly used impingement devices are not very effective and electrostatic precipitation is currently the preferred method at smaller scales up to pilot plant. The vapour product from fluid bed and transported bed reactors has a low partial pressure of collectible products due to the large volumes of fluidising gas, and this is an important design consideration in liquid collection.

Properties of biomass pyrolysis oils

Pyrolysis liquid is referred to by many names including pyrolysis oil, bio-oil, bio-crude-oil, bio-fuel-oil, wood liquids, wood oil, liquid smoke, wood distillates, pyroligneous tar, pyroligneous acid, and liquid wood. The crude pyrolysis liquid is usually dark brown and free flowing with a distinctive smoky smell. Chemically, it approximates to biomass in elemental composition and is composed of a very complex mixture of oxygenated hydrocarbons with an appreciable proportion of water from both the original moisture and reaction product. Solid char may also be present [22].

The physical properties of bio-oils are described in several publications [23-25]. These properties result from the chemical composition of the oils, which is significantly different from that of petroleum-derived oils. Bio-oils are multi-component mixtures comprised of different size molecules derived primarily from depolymerization and fragmentation reactions of three key biomass building blocks: cellulose, hemicellulose, and lignin. Therefore, the elemental composition of bio-oil resembles that of biomass rather than that of petroleum oils. Basic data for bio-oils and conventional petroleum fuels are compared in tab. 2 and those most important for combustion are discussed below. More detail on fuel-related characteristics is provided in [26].

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Table 2. Summary of typical properties and characteristics of wood derived crude bio-oil

Physical property	Typical value	Notes
Moisture content	25%	Water comes from moisture in the feed and reaction water and cannot be separated. Values can range from 15 to 35%
pH	2.5	The low pH comes from organic acids
Density	1.20	Very high at around 1.2 kg/l compared to light fuel oil at around 0.85 kg/l. Bio-oil has about 40% of the energy content of fuel oil on a weight basis, but 60% on a volumetric basis
Elemental analysis		Typically: C: 57%, H: 6.0%, O: 37%, N: trace; Ash; trace depending on char content
Ash	0%	All ash is associated with the char
HHV as produced (depends on water)	18 MJ/kg	Bio-oil has a higher heating value of about 18 MJ/kg as produced with about 25% wt. water that cannot be separated
Viscosity (at 40 °C and 25% water)	50 cp	Viscosity as produced can vary from 20 cSt to as high as 1000 cSt (measured at 40 °C) depending on feedstock, water content, light and ageing
Solids (char)	0.2%	0.1 wt.% is a good level and 1% is often encountered
Vacuum distillation residue	50%	Cannot be completely vaporised. Heating to 100 ºC causes production of a solid residue of around 50 wt.% of the original liquid and distillate containing volatile organics and water
Appearance		Typically a dark brown free flowing liquid
Odour		A distinctive smoky smell
Miscibility		Water addition can be tolerated up to about 35% wt. Bio-oil is miscible with polar solvents such as methanol, but totally immiscible with petroleum-derived fuels

The oxygen content of bio-oils is usually 45-50 wt.%. This oxygen is present in most of the more than 300 compounds that have been identified in the oils. The distribution of these compounds mostly depends on the type of biomass used and on the process severity (temperature, residence time, and heating rate profiles). An increase in pyrolysis severity reduces the organic liquid yield due to cracking of the vapours and formation of gases but leaves the organic liquid with less oxygen. The single most abundant bio-oil component is water. The other major groups of compounds identified are hydroxyal-

dehydes, hydroxyketones, sugars, carboxylic acids, and phenolics. Most of the phenolic compounds are present as oligomers having a molecular weight ranging from 900 to 2500 [27].

The presence of oxygen in many oil components is the primary reason for differences in the properties and behaviour seen between hydrocarbon fuels and biomass pyrolysis oils. The high oxygen content results in a low energy density (heating value) that is less than 50% of that for conventional fuel oils and immiscibility with hydrocarbon fuels. An even more important consequence of the organic oxygen is the instability of bio-oil, which will be discussed later.

Water in bio-oils results from the original moisture in the feedstock and as a product of the dehydration reactions occurring during pyrolysis [28]. Therefore, the water content varies over a wide range (15-35%) depending on the feedstock and process conditions. At this concentration water is usually miscible with the oligomeric lignin-derived components because of the solubilizing effect of other polar hydrophilic compounds (low-molecular-weight acids, alcohols, hydroxyaldehydes, and ketones) mostly originating from the decomposition of carbohydrates. The presence of water has both negative and positive effects on the oil properties. It lowers its heating value, especially the LHV and flame temperature. It also contributes to the increase in ignition delay and in some cases to the decrease of combustion rate compared to diesel fuels [28]. On the other hand, it improves bio-oil flow characteristics (reduces the oil viscosity), which is beneficial for combustion (pumping and atomization). It also leads to a more uniform temperature profile in the cylinder of a diesel engine and to lower NO_x emissions.

Due to their chemical composition bio-oils show a very wide range of boiling temperature. In addition to water and volatile organic components, biomass pyrolysis oils contain substantial amount of non-volatile materials such as sugars and oligomeric phenolics. In addition, the slow heating of the oils during distillation results in polymerization of some reactive components. Consequently, the oils start boiling below 100 °C but the distillation stops at 250-280 °C leaving 35-50% of the starting material as residue. Thus, bio-oils cannot be used for applications requiring complete evaporation before combustion.

The viscosity of bio-oils can vary over a wide range (35-1000 cP at 40 °C) depending on the feedstock and process conditions, and especially on the efficiency of collection of low boiling components. It decreases at higher temperatures much faster than for petroleum-derived oils so even very viscous bio-oils can be easily pumped after a moderate preheating. A significant reduction in viscosity can also be achieved by addition of polar solvents such as methanol or acetone. An undesired effect, especially observed when the oils are stored or handled at higher temperature, is the viscosity increase with time [29]. This is believed to result from chemical reactions between various compounds present in the oil leading to the formation of larger molecules. There is also evidence of reaction with oxygen from air.

Bio-oils contain substantial amounts of organic acids, mostly acetic and formic acid, which results in a pH of 2-3. For this reason the oils are corrosive to common construction materials such as carbon steel and aluminum [30] and can affect some sealing materials. The corrosiveness is especially severe at elevated temperature and with the in-

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crease in water content. The oils are essentially non-corrosive to stainless steels. Polyolefins are usually an acceptable material of construction where other circumstances permit.

These properties have an important impact on the behaviour of bio-oils during combustion and consequently on the applications for energy production in standard equipment. Bio-oils are combustible but not flammable; because of the high content of non-volatile components bio-oil requires significant energy for ignition but once ignited, it burns with a stable self-sustaining flame. An extensive study on the fundamentals of bio-oil combustion was done at Sandia National Laboratory using bio-oils produced at the NREL vortex reactor plant [31, 32]. Combustion tests performed on single droplets demonstrated a very unique, multi-step process comprised of the following phases: ignition, quiescent burning (blue), droplet micro-explosion, disruptive sooty burning of droplet fragments (bright yellow), and formation and burnout of cenosphere particles. In contrast, petroleum distillate fuel oil demonstrated in the same conditions only quiescent, sooty burning from ignition through burnout. Despite large differences in fuel properties and combustion mechanisms, the burning times of bio-oils were comparable to those of No. 2 fuel oil under the same conditions. While the droplets of less severely cracked pyrolysis oils were found to exhibit an earlier but less effective micro-explosion and significantly longer burnout times than No. 2 fuel oil (180 ms *vs*. 110 ms), the bio-oils that underwent more severe cracking during the pyrolysis process exhibited more violent micro-explosions, which resulted in more rapid burnout than light fuel oil. Also the adiabatic flame temperature for bio-oil is relatively high, 1700-2000 K compared to 2200-2300 K for standard fuels. This difference is much less than could be expected based on heating values because of significantly lower stoichiometric air-to-fuel ratio for biomass pyrolysis oils (about 7 compared to 14 for standard fuels).

Macro-scale combustion tests performed in flame tunnels at MIT [33] and CANMET [34] on fast pyrolysis bio-oil as well as those done at the International Flame Research Foundation [35], ENEL [36], and COGIS [37] using slow pyrolysis liquid did not indicate fundamental differences in combustion behaviour of wood pyrolysis oil and No. 2 fuel oil and confirmed that bio-oil could be burned with steady, self-sustaining flames similar to those from petroleum-based fuel oils. Emissions from bio-oil combustion, in general, showed higher particulate and CO levels than for petroleum fuels with NO_x concentration less than for No. 6 but higher than for No. 2 fuel oil.

Liquid product characteristics

The liquid is formed by rapidly quenching and thus "freezing" the intermediate products of flash degradation of hemicellulose, cellulose and lignin. The liquid thus contains many reactive species, which contribute to its unusual attributes. Bio-oil can be considered a micro-emulsion in which the continuous phase is an aqueous solution of holocellulose decomposition products that stabilizes the discontinuous phase of pyrolytic lignin macro-molecules through mechanisms such as hydrogen bonding. Aging

Table 3. Typical properties and characteristics of wood derived crude bio-oil

Appearance	Pyrolysis oil typically is a dark brown free flowing liquid. Depending upon the initial feedstock and the mode of fast pyrolysis, the colour can be almost black through dark red-brown to dark green, being influenced by the presence of micro-carbon in the liquid and by the chemical composition. Hot vapour filtration gives a more translucent red-brown appearance due to the absence of char. High nitrogen contents in the liquid can give it a dark green tinge.
Odour	The liquid has a distinctive odour – an acrid smoky smell, which can irritate the eyes if exposed for a prolonged period to the liquids. The cause of this smell is due to the low2 molecular weight aldehydes and acids. The liquid contains several hundred different chemicals in widely varying proportions, ranging from formaldehyde and acetic acid to complex high molecular weight phenols, anhydrosugars and other oligosaccharides.
Miscibility	The liquid contains varying quantities of water which forms a stable single phase mixture, ranging from about 15 wt.% to an upper limit of about 30-50 wt.% water, depending on how it was produced and subsequently collected. Pyrolysis liquids can tolerate the addition of some water, but there is a limit to the amount of water, which can be added to the liquid before phase separation occurs, in other words the liquid cannot be dissolved in water. It is miscible with polar solvents such as methanol, acetone, *etc*. but totally immiscible with petroleum--derived fuels.
Density	The density of the liquid is very high at around 1.2 kg/l compared to light fuel oil at around 0.85 kg/l. This means that the liquid has about 42% of the energy content of fuel oil on a weight basis, but 61% on a volumetric basis. This has implications on the design and specification of equipment such as pumps.
Viscosity	The viscosity of the bio-oil as produced can vary from as low as 25 cSt to as high as 1000 cSt (measured at 40 °C) or more depending on the feedstock, the water content of the oil, the amount of light ends that have been collected and the extent to which the oil has aged. Viscosity is important in many fuel applications [38].
Distillation	Pyrolysis liquids cannot be completely vaporised once they have been recovered from the vapour phase. If the liquid is heated to 100 ºC or more to try to remove water or distil off lighter fractions, it rapidly reacts and eventually produces a solid residue of around 50 wt% of the original liquid and some distillate containing volatile organic compounds and water. The liquid is, therefore, chemically unstable, and the instability increases with heating, so it is preferable to store the liquid at room temperature. These changes do also occur at room temperature, but much more slowly and can be accommodated in a commercial application.
Aging of pyrolysis liquid	The complexity and nature of bio-oil causes some unusual behaviour, specifically that the following properties tend to change with time: - viscosity increases, - volatility decreases, and - phase separation and deposition of gums can occur.

or instability is believed to result from a breakdown in this emulsion. In some ways it is analogous to asphaltenes found in petroleum.

Fast pyrolysis liquid has a higher heating value of about 17 MJ/kg as produced with about 25 wt.% water that cannot readily be separated. The liquid is often referred to as "oil" or "bio-oil" or "bio-crude" although it will not mix with any hydrocarbon liquids. It is composed of a complex mixture of oxygenated compounds that provide both the potential and challenge for utilisation. There are some important characteristics of this liquid that are discussed briefly in tab. 3.

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Applications for bio-oil

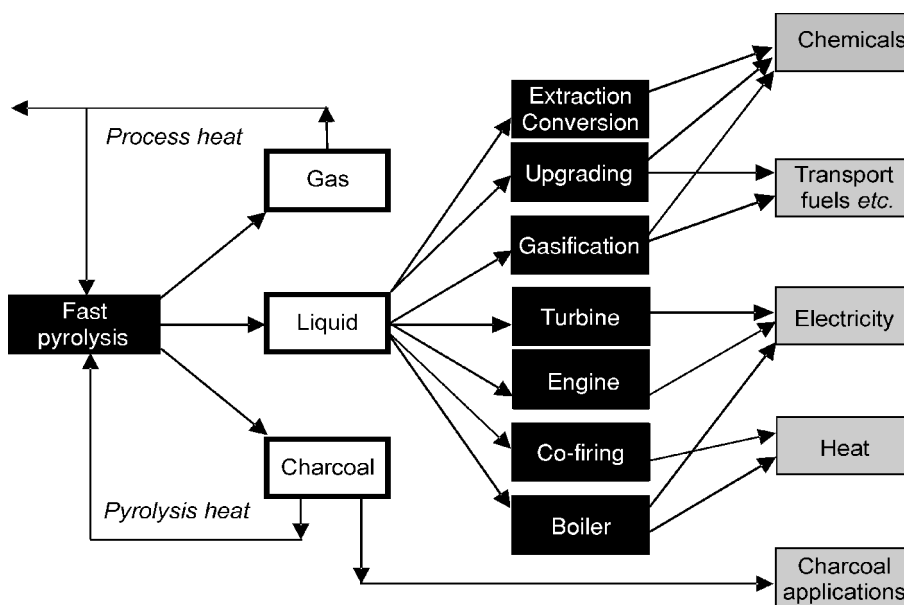The range of applications for all the products from fast pyrolysis is summarized in fig. 2.

Figure 2. Fast pyrolysis and uses of the products

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Fuel applications of bio-oils

Over the last two decades there has been a growing interest in using biomass-derived fuels. Initially this interest was driven by concerns for potential shortages of crude oil, but in recent years the ecological advantages of biomass fuels have become an even more important factor. Biomass fuels can be considered essentially CO_2 neutral and have a very low sulphur content compared to many fossil fuels. In addition, being a liquid, bio-oil can be easily transported and stored. However, the properties of bio-oil also result in several significant problems during its use as fuel in standard equipment such as boilers, engines, and gas turbines constructed for combustion petroleum-derived fuels. Poor volatility, high viscosity, coking, and corrosiveness are probably the most challenging and have so far limited the range of bio-oil applications. In addition, bio-oil is not yet a commercial product and it lacks the quality standards necessary for commercial application.

The variability of its composition due to different feedstocks, reactor configurations, and recovery systems that results in differences in physical and chemical properties as well as combustion behaviour makes large-scale applications even more difficult. However, compared to traditional biomass fuels such as black liquor or hog fuel, bio-oil presents a much better opportunity for high-efficiency energy production and significant effort has been spent on research and development directed to the application of bio-oil for the generation of heat and power and for use as a transport fuel. In this paper we review the state of the art in the area of combustion of bio-oil in boilers, diesel engines, gas turbines, Stirling engines and upgrading to potential transport fuel.

Combustion in burner/furnace and burner/boiler systems

Furnaces and boilers are common devices used for heat and power generation. They are usually less efficient than engines and turbines but they can operate with a great variety of fuels ranging from natural gas and petroleum distillates to saw dust and coal/water slurries. Bio-oil seems thus to be a suitable boiler fuel as long as it has consistent characteristics, provides acceptable emissions level, and is economically feasible. Therefore, several companies have been interested in using bio-oil, especially for district heating to replace heavy fuel oil.

The only commercial system that regularly uses bio-oil to generate heat is at the Red Arrow Products pyrolysis plant in Wisconsin [39] and has been operated for over ten years. The 5 MW_t swirl burner uses different mixtures of by-products, water insoluble fraction of bio-oil (pyrolytic lignin), char and gas from the plant dedicated to produce food-flavouring components. The bio-oil fraction is delivered to the combustor through a stainless steel nozzle and atomized with air while char and gas are fed using separate lines. A 600 m^2 exhaust gas/air heat exchanger located at the combustor exit provides all space heating needs for the plant. Emission tests performed in 1994 showed CO at 17%, NO_x at 1.2%, and formaldehyde at 0.2% of the permitted levels.

Most research on bio-oil combustion in boilers has been carried out in Finland. Extensive tests have been performed at Neste Oy [40] in a 2.5 MW Danstoker boiler supplied with a dual fuel burner. The boiler operated satisfactorily in a dual fuel mode at different fuel oil to bio-oil ratios. The operation on pyrolysis oil without the auxiliary fuel required only relatively minor modifications to improve combustion stability. With such modifications emissions of CO and NO_x were at acceptable levels (30 ppm and 140 ppm respectively) but particulates were still high (2.5-5 in Bacharach scale). VTT Energy in collaboration with Oilon Oy [41] performed a series of tests on a wide range of bio-oils in an 8 MW_t nominal capacity furnace operated at 4 MW_t output. The main findings of these tests, which were consistent with those of Neste Oy, can be summarized as follows:

- Some modifications of the burner and boiler sections were required to improve combustion,
- The flame from bio-oil combustion was longer than that from burning standard fuel oil,
- A support fuel was necessary during start up and, in cases of lower quality bio-oils, even during operation,
- There were clear differences in combustion behavior and emissions for different bio-oils tested; those with high viscosity and water and solids content showed significantly worse performances, and
- Emissions, in general, were lower than from burning heavy fuel oil except for particulates. They strongly depended on the proper handling of bio-oil (optimum was preheating to 50 °C and compressed air atomization) and its quality, for example, higher water content lead to lower NO_x but higher particulates in flue gases.

An attractive option can be co-firing of bio-oil with fossil fuels. Large-scale tests have been carried out at the Manitowac power station [42], where pyrolysis liquids from the Red Arrow operation were co-fired with coal for the commercial production of electricity. During a one-month period, bio-oil was co-fired for about 370 hours providing 5% of the thermal input to the 20 MW_e boiler. The combustion of bio-oil was clean and efficient with no adverse changes on the boiler operation or on the emission levels.

In conclusion, a constant and better quality bio-oil available at attractive price is necessary for commercial, large-scale applications. Problems of handling (storage, pumping, filtration, atomization) and optimization of the burner/boiler design to improve performances and reduce emissions seem to be possible to solve by relatively minor modifications to the existing equipment.

Combustion in diesel engines

While boilers are mostly used to produce heat, Diesel engines offer a high efficiency (up to 45%) in power generation and can also be adapted to the combined heat and power process (CHP). Medium and slow speed engines are known for fuel flexibility and can operate on low-grade fuels. The main concerns for operating diesel engines on bio-oils are some specific properties of these liquids such as difficult ignition (resulting

from low heating value and high water content), corrosiveness (acids), and coking (thermally unstable compounds). However, potential advantages of using bio-oils for power generation have led to important research activities in several countries.

In 1993 at VTT Energy, Solantausta *et al.* [43] using a 500 cc (maximum power 4.8 kW) high-speed, single cylinder, direct injection Petter diesel engine with compression ratio of 15.3:1, could not achieve auto-ignition of bio-oil without additives. A minimum of vol. 5% of a nitrated alcohol was required for stable engine operation (typically, 0.1-1 vol.% of this component is added to standard fuels). Even with 9% of this additive, the ignition delay for bio-oil was 9 crank angle degrees (CAD), compared to 6 CAD for No. 2 fuel oil. In addition, coke formed during bio-oil combustion resulting in rapid clogging of injection nozzles. CO, NO_x, and hydrocarbon emissions (after catalytic converter) from pyrolysis oil were comparable to those from diesel fuels. Further tests at VTT Energy [44] (84 kW_e engine) and Wärtsilä [45] (1.5 MW_e engine) showed that bio-oil could be efficiently used in pilot-ignited medium speed diesel engines. The most important identified problems were difficulty in adjusting the injection system (excessive variability in composition of bio-oil), wear and corrosion of certain injection and pump elements (acids, particulates), and high CO emissions. However, it seems possible to overcome these problems with improvements to the pyrolysis process and use of better materials for injection nozzles and a catalytic converter for exhaust gases.

Suppes [46] at University of Kansas found that ignition delay of a hot-filtered bio-oil (no particulates) measured in a combustion bomb was similar to that of 27 Cetane reference fuel. His tests on a blend of 72% pyrolysis oil, 24% methanol, and 4% cetane enhancer (tetraethyleneglycol dinitrate) performed in a single-cylinder, air cooled Lister Petter diesel engine showed the same performance as for diesel oil [47]. The study concluded that the application of pure pyrolysis oils should be limited to low speed diesel engines with relatively high compression ratios but blends of biomass oil and methanol could be used in high-speed engines, especially with cetane improving additives.

Shihadeh [48] at MIT tested the combustion behaviour of biomass pyrolysis oils using a 0.45 l Ricardo single-cylinder direct injection diesel engine operating at compression ratio of 19.8 and 2400 rpm. The tests showed that combustion of bio-oils was predominantly kinetically controlled as opposed to the mixing-controlled combustion of diesel fuel. However, despite those differences, the thermal efficiency of bio-oils was approximately equal to that for diesel fuel, which has been confirmed by Ormrod [49]. Bio-oils required air pre-heating (55 °C) to ignite but the engine operated smoothly even though the ignition delay (6-14 CAD) was longer than for diesel fuel. Hot-filtered bio-oils showed improved combustion characteristics (shorter ignition delay, shorter burn duration, less coking) mostly due to lower molecular weights resulting from vapor cracking during filtration and lower water content.

Ormrod Diesels [50] in the United Kingdom have accumulated more than 400 hours of operation on a modified dual fuel slow speed diesel engine. Three cylinders of the six-cylinder 250 kW_e engine have been modified to run on bio-oil using up to 5% diesel as a pilot fuel to initiate combustion. Emissions other than CO were below those obtained while running on diesel fuel. The engine has been successfully operated entirely on bio-oil by shutting off the diesel supply to the un-modified cylinders [49]. The mini-

mum diesel contribution as a pilot fuel to provide satisfactory operation was 5% in energy terms. Although black deposits formed on the pumps and injectors, these did not appear to affect performance in any way.

Baglioni *et al*. [51] at Pasquali Macchine Agricole (Italy) conducted a series of tests on emulsions of bio-oil in diesel fuel using a 6.25 kW single-cylinder engine (Lombardini 6LD400). They were able to operate the engine using emulsions with up to 50% of bio-oil. The main problems were deposits and erosion of the injectors. Recently Chiaramonti *et al*. [52] used bio-oil-diesel emulsions in four different engines and observed significant damage of the injectors and the fuel pumps, greater than that reported for pure bio-oil.

Combustion in turbines

Gas turbines are used in a wide range of applications, most important of which are driving electric power generators and providing power to aircraft. Accordingly, the two main categories of turbines in use are industrial and aircraft types. However, both types of turbines are used in power plants. Though at present most gas turbines operate on petroleum distillates or gas fuels, if properly designed, they can essentially burn any fuel. Certainly, gas turbines can be modified or redesigned to accommodate some of the unusual properties of biomass pyrolysis oils. Moses [53] pointed out that modifications have to be done considering the effects of physical and chemical properties of bio-oils on atomization, combustion efficiency, soot formation, and gaseous and particulate emissions. Also very important issues to address are compatibility of bio-oils with the materials used in fuel systems (acid corrosion) and in blades (erosion, alkali hot corrosion).

The first gas turbine tests on biomass slow pyrolysis liquids were carried out at Teledyne CAE (USA) by Kasper *et al*. [54] in early1980s using a J69-T-29 gas turbine combustor rig. The system consisted of an annular combustor and a centrifugal fuel injector rotating at shaft speed. The centrifugal injector was designed to provide good atomization of viscous fuels. The pyrolysis liquids used in the tests were produced from forest and agricultural residues and resembled typical fast pyrolysis bio-oils though they had higher carbon content and higher viscosity. The measured combustion efficiency in the rig using pyrolytic oil as fuel was 95% but it was expected it could exceed 99% in the engine at optimum conditions. Emissions of CO were higher but CH and NO_x were within the limits observed for petroleum fuels. Also a slag build up in the exhaust section resulting from ash in bio-oil was identified as a potential problem.

Since 1995 Orenda Aerospace Corporation (Canada) has been actively working on the application of bio-oil in gas turbines combustion. They selected a 2.5 MW_e class GT2500 engine that was designed and built by Mashproekt in Ukraine as the most suitable for low-grade fuels including bio-oil. The main advantage of this engine is its "silo" type combustion chamber located above the turbine that can be easily modified and optimized for any fuel. Also, advanced coating of the whole hot section provides protection against contaminants (alkali). Andrews *et al*. [55] tested the engine throughout the whole

operational range, from idle to full power, and found that NO_x and SO_2 emissions from combustion bio-oil were less while particulates were higher than those from diesel fuel.

Strenziok *et al.* [56] at the University of Rostock (Germany) conducted bio-oil combustion tests in a small commercial gas turbine T216 with a rated electric power output of 75 kW$_e$. The combustion chamber of the turbine was modified and supplied with two separate fuel systems that included an ignition nozzle for diesel fuel and a main nozzle for bio-oil. The engine operated in a dual fuel mode at 73% of the full power that would be generated in a standard fuel mode, with about 40% of total power produced from bio-oil and 60% from diesel. Compared to the operation on diesel fuel, CO and HC emissions were significantly higher and NO_x less for dual fuel operation. The use of bio-oil in the turbine resulted in deposits in the combustion chamber and on the blades and finding a solution to prevent fouling of the turbine is a priority requirement.

Combustion in Stirling engines

Recently, in addition to boilers, diesel engines, and turbines, Stirling engines, which are suitable for small-scale CHP production have been considered for the application of bio-oil as an alternative fuel. Bandi and Baumgart [57] at ZSW (Germany) used bio-oil in a 25 kW Stirling CHP unit supplied with a modified FLOX® (flameless oxidation) burner that included an air pressure atomizer. The tests proved that bio-oil could be efficiently burned in such a burner without noticeable residues and with emissions below German standards. Electrical and thermal efficiencies of the CHP unit were not very satisfactory (50-60% overall) possibly because of the burning chamber geometry and not preheating air for atomization.

Upgrading of bio-oil to transport fuels

The properties that negatively affect bio-oil fuel quality are foremost low heating value, incompatibility with conventional fuels, solids content, high viscosity, incomplete volatility, and chemical instability. Some of those deficiencies can be improved using relatively simple physical methods while others require more complex chemical processing. Maggi and Elliott [58] extensively reviewed the upgrading methods of bio-oils. In this paper, we will only discuss those that can lead to the use of bio-oil as transport fuel.

The simplest use of bio-oil as a transport fuel seems to be in combination with diesel fuel. Although biomass pyrolysis oils are not miscible with hydrocarbons, with the aid of surfactants they can be emulsified with diesel fuel. Processes for producing stable micro-emulsions with 5-30% of bio-oil in diesel have been developed at CANMET [59] (Canada) and at the University of Florence [51, 38] where emulsions from 10 to 90% bio-oil in diesel were produced. The resultant emulsions showed promising ignition characteristics. A drawback of this approach is the cost of surfactants and the high energy re-

quired for emulsification. In addition significantly higher levels of corrosion/erosion were observed in engine applications than with bio-oil or diesel alone.

Upgrading bio-oil to a conventional transport fuel requires full deoxygenation, which can be accomplished by two main routes: hydrotreating and catalytic vapour cracking. Hydrotreating of bio-oil carried out at high temperature, high hydrogen pressure, and in the presence of catalysts results in elimination of oxygen as water and in hydrogenation-hydrocracking of large molecules. The catalysts (typically sulphided CoMo or NiMo supported on alumina) and the process conditions are similar to those used in the refining of petroleum cuts [60]. Chemical methods for upgrading bio-oil by hydrotreating and zeolite cracking have been reviewed by Bridgwater [61, 62]. A projected typical yield of naphtha equivalent from biomass is about 25% by weight or 55% in energy terms excluding provision of hydrogen [62].

Catalytic vapour cracking makes deoxygenation possible through simultaneous dehydration-decarboxylation over acidic zeolite catalysts. At 450 °C and atmospheric pressure, oxygen is rejected as H_2O, CO_2, and CO producing mostly aromatics [63]. The low H/C ratio in the bio-oils imposes a relatively low limit on the hydrocarbon yield and, in addition, the technical feasibility is not yet completely proven. Catalyst deactivation still raises many concerns for both routes, although the coking problem with zeolites can in principle be overcome by a conventional FCC arrangement with continuous catalyst regeneration by oxidation of the coke. Some concern has been expressed over the poor control of molecular size and shape with orthodox zeolites and the propensity for formation of more noxious hydrocarbons [64]. The processing costs are high and the products are not competitive with fossil fuels [65]. A projected typical yield of aromatics suitable for gasoline blending from biomass is about 20% by weight or 45% in energy terms [62].

Although upgrading to a liquid transport fuel does not currently look promising, bio-oil can become a source of the emerging transport fuel for the future – hydrogen. Production of hydrogen from biomass by pyrolysis and reforming has been extensively studied at the National Renewable Energy Laboratory (USA) [66, 67]. The water-soluble (carbohydrate-derived) fraction of bio-oil was efficiently converted to hydrogen and CO_2 (>80% of theoretical conversion) in a fluidized bed process using commercial, nickel-based catalysts in the conditions similar to those for reforming natural gas. In such a concept, only 6 kg of hydrogen were produced from 100 kg biomass compared with 11-12 kg that could be obtained by direct gasification of biomass. However, the process makes economical sense providing that the lignin-derived fraction of bio-oil could be sold at half the price of phenol for the use as a phenol replacement in phenol-formaldehyde resins [68].

An alternative approach has recently been proposed whereby bio-oil or a bio-oil/char slurry is used as an energy carrier to more economically transport biomass to a central processing site where the liquid or slurry is gasified in an oxygen blown pressurized gasifier to syngas for production of liquid fuels [69]. This offers the possibility of achieving high throughputs to take advantage of the economy of scale that is often absent in stand-alone bio-energy plants.

Summarizing, the application of bio-oils for heat and power generation is possible and usually only requires minor modifications of the existing equipment as demon-

strated by the tests in boilers, diesel engines, and turbines. More research is needed in the area of handling bio-oils, especially on stabilization. Upgrading bio-oil to a quality transport liquid fuel still poses several technical challenges and is not currently economically attractive. An attractive future transportation fuel can be hydrogen produced by steam reforming of the whole oil or its carbohydrate-derived fraction.

Applications of bio-oil for producing chemicals

For many centuries wood pyrolysis liquids were a major source of chemicals such as methanol, acetic acid, turpentine, tars, *etc*. At present, most of these compounds can be produced at a lower cost from other feedstocks derived from natural gas, crude oil or coal. Though over 300 compounds have been identified in wood fast pyrolysis oil their amounts are small and isolation of specific single compounds is seldom practical or economic as it usually require complex separation techniques. Therefore, the development of technologies for producing products from the whole bio-oil or from its major, relatively easy separable fractions is the most advanced. In this paper we will discuss only the existing and potential short-term applications of bio-oil for producing chemicals. A more detailed review on this subject, including consideration of higher-value products, was published by Radlein [70].

Chemicals produced from the whole bio-oil

The whole bio-oil can be converted into useful chemicals by taking advantage of its most abundant functional groups: carbonyl, carboxyl, and phenolic and react them in such a way that the non-reacting part of bio-oil would not have to be separated from the final product. For example, carboxylic acids and phenols can easily react with lime to form calcium salts and phenates. Based on this property, Dynamotive Corporation developed a product, BioLime [71], which proved successful in capturing SO_x emissions from coal combustors. BioLime that typically contains 50% water and 7-14% calcium by weight is injected as a liquid suspension into high-temperature flue gas stream. Compared to lime, those organic calcium compounds are about four times more efficient in capturing acid gases. With appropriate calcium to sulfur ratio BioLime can remove 90-98% SO_x from flue gases. Another advantage of BioLime is that oxidation of its organic, bio-oil derived part provides additional energy in the combustor. Furthermore, some components of BioLime proved to be efficient in destroying nitrogen oxides [72]. Although the technology for producing BioLime is well developed, the availability of low-cost lime makes marketing difficult.

Another promising application of the whole bio-oil exploits its high content of carbonyl groups. By reacting bio-oil with ammonia, urea or other $-NH_2$ containing materials various imide and amide bonds are formed between carbonyl carbons and nitrogen. In this fashion about 10% nitrogen can be incorporated in an organic matrix that proved to have properties of an efficient biodegradable slow-release nitrogen fertilizer [73, 74].

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Compared to mineral fertilizers, such a product has lower leachability, which results in less pollution of ground waters. In addition, it is a good soil conditioning material containing humic type matter (lignin). Application of such a fertilizer returns carbon to the soil and can be also considered a method of carbon sequestration. Typical controlled-release nitrogen fertilizers sell for 250-1250 $/ton, so bio-oil based fertilizer should be cost competitive on the market and is targeted for commercialization by DynaMotive [75].

In addition to the above applications, the whole bio-oil has been recently proposed for use as an alternative wood preservative that could replace creosote [76]. Some terpenoid and phenolic compounds present in bio-oil are known to act as insecticides and fungicides. It was proven that impregnating with bio-oil protects wood from fungi [77], however the efficiency of bio-oil action was not long lasting. When the retention of bio-oil in wood is improved, either the whole liquid or a fraction could be used as an environmentally friendly wood preservative.

Chemicals from fractionation of bio-oil

Bio-oil can be easily separated into two fractions based on water solubility. By simple water addition to bio-oil, a viscous mostly oligomeric lignin-derived fraction settles at the bottom while water soluble, mostly carbohydrate-derived compounds form a top layer. Although other solvent fractionation methods have also been developed, especially to improve the purity of the lignin-derived material [78], water addition seems to be the favoured option.

The water-soluble part of fast pyrolysis bio-oil has found an application that has been commercial for over ten years. The aqueous extract of bio-oil includes both low-molecular weight aldehydes that are effective meat browning agents (especially glycolaldehyde) as well as phenolic compounds that provide smoky flavours. Based on this, a range of food flavoring compositions have been patented and commercialized by Red Arrow Products Company [79-81], that successfully competes with similar products known as "liquid smoke" produced by a variety of slow pyrolysis processes in several countries.

A potential application of the water-soluble fraction of bio-oil is the production of calcium salts of carboxylic acids that can be used as environmentally friendly road de-icers [82]. Volatile organic acids, mostly formic, acetic, and propionic that are abundant in the aqueous extract of bio-oil can be distilled off as a sub-fraction. Although such a distillate also includes other volatile components (such as aldehydes and esters), they either can react with lime or are evaporated during the recovery of solid calcium salts. The scale up of the production of biomass-derived de-icers is technically feasible but not currently economic. Calcium chloride is much less expensive and thus used as the most common de-icer though it is known to have deleterious effects on plants.

The water insoluble fraction that usually constitutes 25-30% of the whole bio-oil is often called pyrolytic lignin because it is essentially composed of oligomeric fragments originating from degradation of native lignin [83, 84]. So far, high value applications of this fraction have not been commercialized, however, using pyrolytic lignin as

phenol replacement in phenol-formaldehyde resins seems to approach that stage. The most important contributions in research and development on pyrolitic lignin based resin formulation have been made at NREL [85, 86], and Biocarbons [87] in the USA, Ensyn [88] and Pyrovac [89] in Canada, and ARI (now Chimar Hellas) [90] in Greece. Although lignin is less reactive than phenol, 30-50% of phenol can be replaced by pyrolytic lignin in novolak and resole formulations producing high-quality resins. Those resins were successfully used as adhesives in plywood and particleboard manufacturing showing high mechanical strength. Lower toxicity and lower cost compared to phenol make pyrolytic lignin an attractive component of adhesives. Consequently, resin and board manufacturers such as Louisiana Pacific, Weyerhauser, A.C.M. Wood Chemicals, and others have been heavily involved in commercialization of bio-oil derived adhesives.

Specific chemicals from bio-oil

As mentioned above, the production of specific chemicals from bio-oil is possible but because of the complexity of separation techniques has not been developed in larger scale, except from slow pyrolysis liquids where viable production of a few specific chemicals by companies such as Chemviron in Germany, and until 2002, Usine Lambiotte in France. The most promising seems to be glycolaldehyde (also known as hydroxyacetaldehyde) that is besides water the most abundant single component of fast pyrolysis bio-oil. Glycolaldehyde is also the most active meat-browning agent in "liquid smoke" and, therefore, it raised interests in food flavoring industry. Red Arrow Products [91] and RTI [92] patented methods for isolation of glycolaldehyde based on crystallization. The production of glycolaldehyde is more attractive if cellulose is used instead of wood as feedstock for fast pyrolysis. In such a case the lignin-free pyrolysis liquid contains higher concentration of the desired product and isolation is easier, more efficient and has been shown to be more economic, even allowing for the higher cost of cellulose compared to biomass [93].

Levoglucosan (1,6-anhydro- -D-glucopyranose) and levoglucosenone (6,8-dioxabicyclo[3.2.1.]oct-2-en-4-one) are not typical components of bio-oil produced for fuel application but can be generated with high yields by a similar pyrolysis processes from demineralized cellulose or biomass. For example, Dobele [94] reported that 46% yield of levoglucosan and 24% of levoglucosenone were obtained by fast pyrolysis (pyroprobe) of acid pretreated cellulose. A substantial review on the production and potential applications of levoglucosan was published by Radlein [95]. Several processes have been patented for pyrolytic generation, recovery and purification of levoglucosan from cellulose and lignocellulosic materials, for example the University of Waterloo fluidized bed process [96]. The optimum process temperature for the production of levoglucosan is in the range of 400-500 °C and different types of reactors can be used to provide about 50% yield based on cellulose in the feedstock. In the former Soviet Union a 20 kg/h fluidized bed and a 30 kg/h cyclonic reactor were used to produce levoglucosan from acid hydrolyzed biomass (lignocellulose) [97]. The approximate yield of levoglucosan from fast pyrolysis of lignocellulose was 20% in the condensate and 10% as a

purified (96%) product. It seems that the main difficulty in the production of levoglucosan is not pyrolysis but rather its efficient isolation from the pyrolytic liquids. Though levoglucosan has potential for the manufacturing of pharmaceuticals, surfactants, biodegradable polymers, and others the high production price mostly due to the lack of low-cost recovery and purification procedures makes unlikely its extensive use in the near future. Levoglucosenone was produced by fluidized bed pyrolysis of phosphoric acid impregnated cellulose with the yield of 24% [70]. It can be relatively easily recovered from pyrolytic liquid by distillation. As with levoglucosan, it has potential in the synthesis of antibiotics and flavour compounds, but has not found yet a large-scale application.

In summary, some chemicals produced from the whole bio-oil or by its fractionation are already commercial products, for example liquid smoke, or have a chance for short-term commercialization, especially if a bio-refinery concept based on fast pyrolysis process is implemented [98]. Commercialization of specialty chemicals from bio-oil requires more work on developing reliable low-cost separation procedures as well as working more closely with potential market outlets.

Barriers

The technologies and applications have to overcome a number of technical and non-technical barriers before industry will implement their commercialisation and usage. The technical barriers have been described above, while some of the more important non-technical barriers are summarised below.

Economics

All bio-fuels have to compete with fossil fuels. For those countries who have made commitments to reduce fossil fuel derived carbon emissions, the current disincentive to implementation of bio-energy on simple cost grounds will have to be overcome – no company is going to invest in ventures that are guaranteed to lose money, regardless of the environmental benefits that may accrue. Industry will only invest in technology that has an acceptable return at an acceptable risk [99]. Acceptable returns will come from incentives for capital expenditure or product purchase, or to dis-incentives to orthodox options by, for example taxation on fossil fuels or legislation, *etc*. This is one of the major roles that governments have to play.

Perception

There is widespread approval of the interest in, and move towards, renewal energy and bio-energy – as long as it is not near me! Increasing attention will need to be placed on "selling" the idea to the populace where the plant is to be built, and this prob-

lem could be exacerbated by the need to build smaller plants and thus many more plants than conventional power stations and refineries. Early plants will have the curiosity factor and may enjoy popularity as an attraction by itself or as part of an attraction of a "green" site.

Politics

For industry to implement renewable energy technologies in order that commitments made to mitigate greenhouse gases can be met, investment has to be attractive. Without some fiscal incentives (or disincentives against fossil fuels), companies will only invest in those projects that are sufficiently profitable and most of these will be in niche markets and special opportunities. As commented above, only governments can create the necessary instruments.

Scale

Economies of scale are a vital feature of the development of industry and technology in which the larger a process can be built, the cheaper it becomes. This is particularly important in the energy and process industries that will shoulder the responsibility for technology development and implementation. However in the bio-energy industry, biomass is a diffuse resource which has to be harvested over large areas. A modest 10 MW_e power station operating at a modest efficiency of 35% will require about 40000 t/year of wood on a dry basis which will require about 4000 ha of land or 40 km^2. This could reduce to 2000 ha or 20 km^2 if the promise of high yielding short rotation forestry is realised. Neither figure makes any allowance for non-productive land. There are therefore finite sizes that bio-energy processes can be built in considering the costs and logistics of transporting biomass to a processing plant. The maximum size that has been suggested in Europe ranges from 30 to 80 MW_e in the short to medium term, and 100 to 150 MW_e in North America. This places a practical upper limit on the benefits of scale.

An alternative option is to consider massive trading in biomass such as the suggested 3 GW_e power plant in Rotterdam requiring 30 million t/year biomass imported from places like Brazil. Biomass is already traded extensively round the world, mostly for pulp and paper, so an extension to energy applications only requires establishment of a market and acceptable economics.

Risk

Investors are generally risk averse and always prefer low risk investments, but if risks have to be accepted, then an appropriately higher return is expected. Technology developers can do much to minimise technical risk and this topic has been thoroughly described and discussed [99].

Vested interests

The established energy suppliers and providers have considerable investments in orthodox energy systems and will always seek to maximise their returns and maintain their competitive edge. Most major energy companies have their own programmes of supporting renewable energy, but there have always been concerns over the extent to which they will seek to protect their interests.

Conclusions

The liquid bio-oil product from fast pyrolysis has the considerable advantage of being a storable and transportable fuel as well as a potential source of a number of valuable chemicals that offer the attraction of much higher added value than fuels. Bio-oil has been successfully used as boiler fuel and also showed promise in diesel engine and gas turbine applications. Upgrading bio-oil to a quality of transport liquid fuel still poses several technical challenges and is not currently economically attractive. Some chemicals, especially those produced from the whole bio-oil (such as fertilizers) or its major fractions (such as liquid smoke or for wood resins) offer more interesting commercial opportunities.

There are still many challenges to overcome before bio-oil finds large-scale application as fuel, including:

- Cost of bio-oil, which is 10 to 100% more than fossil fuel in energy terms,
- Availability of bio-oil for applications development remains a problem and there are limited supplies for testing,
- Lack of standards for use and distribution of bio-oil and inconsistent quality inhibits wider usage. Considerable work is required to characterize and standardize these liquids and develop a wider range of energy applications,
- Incompatibility of bio-oil with conventional fuels and, therefore, need for dedicated fuel handling systems,
- Users are unfamiliar with bio-oil,
- Environmental health and safety issues need to be completely resolved, and
- Pyrolysis as a technology does not enjoy a good image.

More research and development is needed in the field of fast pyrolysis and bio-oil testing to develop large-scale applications. The most important issues that need to be addressed seem to be:

- Scale-up,
- Cost reduction,
- Better oil quality,
- Norms and standards for producers and users,
- Environment health and safety issues in handling, transport and usage,
- Encouragement to implement processes and applications, and
- Information dissemination.

Abreviations

HHV   – Higher heating value
LHV   – Lower heating value
CHP   – Combined heat and power production
CAD   – Crank angle degrees

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