



Power generation using fast pyrolysis liquids from biomass

David Chiaramonti^{a,*}, Anja Oasmaa^b, Yrjö Solantausta^b

^aUniversity of Florence, Department of Energy Engineering "S.Stecco", I-50139, Florence, Italy

^bTechnical Research Centre of Finland (VTT), P.O.Box 1601, FIN-02044 VTT, Finland

Received 19 July 2005; accepted 26 July 2005

Abstract

Power production from biomass derived pyrolysis liquids has been under development for the past few years. If technically successful, it would make decentralized bio-energy production possible. Several technologies and system components have been developed by academia, R&D organizations, and industrial companies in many countries. Much experience has been gained and many useful results published. The present work aims at reviewing the most significant experience in power generation from biomass liquids produced by fast pyrolysis processes. Power plant technologies addressed are diesel engines, gas turbines, and natural gas/steam power plants. Main results are reviewed and R&D needs identified for each technology. The analysis shows that even for the most promising solutions long-term demonstration has not yet been achieved. Pyrolysis liquid use in gas

Abbreviations: ASTM, American Society for Testing Materials; BMEP, brake mean effective pressure; BTDC, before top dead centre; BTG, Biomass Technology Group, The Netherlands; CANMET, The Canada Center for Mineral and Energy Technology; CEM, continuous emission monitoring; CC, combustion chamber; Dyglyme, diethyl glycol dimethyl ether; EPDM, ethylene propylene diene; EtOH, ethanol; FLOX[®], Flameless OXidation; FN, flow number; GT, gas turbine; HFO, heavy fuel oil; HVF, hot vapour filtration; IGT, ignition quality test; JP4, kerosene (aviation fuel); LFO, light fuel oil; LHV, lower heating value; MGT, micro gas turbine; MIT, Massachusetts Institute of Technology; NREL, National Renewable Energy Laboratory; NG, natural gas; PDU, process development unit; PGS, power generation system; PL, pyrolysis oil, pyrolysis liquid, bio-oil, bio fuel oil, bio crude oil; PLC, programmable logic controllers; RTPTM, Ensyn Rapid Thermal Process, Canada; SMD, sauter mean diameter; TIT, turbine inlet temperature; VTT, Technical Research Centre of Finland.

*Corresponding author. Tel.: +39 0554796436; fax: +39 0554796342.

E-mail address: d.chiaramonti@ing.unifi.it (D. Chiaramonti).

turbine plants and in co-firing mode in large power stations are technically most advanced. Recent work with diesel engines also appears quite promising.

© 2005 Elsevier Ltd. All rights reserved.

Keywords: Biomass; Pyrolysis; Power; Gas turbine; Engine; Co-firing

Contents

1. Introduction and scope of the work	2
2. Type of fuels and power generation system (PGS) under investigation	3
2.1. Fuels	3
2.2. Power generation systems	8
3. Use of biomass pyrolysis liquid for power generation	8
3.1. Diesel engines	8
3.1.1. Pure PL in diesel engines	8
3.1.2. Blending, emulsions and mixtures of PL with other fuels in diesel engines	11
3.2. Gas turbines	17
3.2.1. Conclusions on PL use in GTs	23
3.3. Co-firing	24
3.4. Other applications of biomass PO for power generation	25
4. R&D needs and conclusions	25
Acknowledgments	27
References	28

1. Introduction and scope of the work

Power produced from biomass has been assessed as one of the leading candidates for reducing CO₂-emissions in power production [1,2]. The most important industrial alternative today is the Rankine cycle using solid biomass. Power plants from less than 1 MWe up to 240 MWe are in operation using biomass fuels. Other existing biomass fuelled power plant concepts apply either gas engines or gas turbines fuelled with biologically (landfill gases, anaerobic digestion gases) or thermally (gasification) derived fuel gases.

However, de-coupling of bulky solid fuel handling from the actual power generating plant would be highly advantageous (Table 1). Fast pyrolysis, in which an effort is made to maximize the liquid product yield from solid biomass, is a potential candidate for power production. Up to about 65 wt% organic liquid yield from dry low-ash biomass has been produced in research units. Since, even from dry biomass, pyrolysis water is always produced, the overall liquid yield from dry biomass may be up to 75 wt%. Feedstock natural moisture will also be present in the liquid product.

Fast pyrolysis of biomass was initially developed from laboratory to Process Development Unit-scale in Canada and USA during the 1980s [3–6]. Since then, the technology has been assessed as a promising biofuel alternative [7–9]. However, several uncertainties remain related to both production and utilization technology. Comprehensive reviews of pyrolysis oil applications have been recently published by Czernik and Bridgwater [10] and Oasmaa et al. [11,12]. However, economic uncertainties concerning the competitiveness of the technology remain as long as no commercial plants are in operation.

Table 1
Advantages of using fast pyrolysis liquids as fuel

-
- Pyrolysis liquid is the lowest cost liquid biofuel, and its CO₂-balance is clearly positive
 - Possibility of utilization in small-scale power generation systems as well as use in large power stations (co-firing)
 - Possibility to decouple solid biofuel handling from utilization (reduced capital and operation costs in utilization)
 - Storability and transportability of liquid fuels
 - High-energy density compared to atmospheric biomass gasification fuel gases
 - Intermittent operation feasible
 - If light fuel oil is replaced, middle distillates are released to be used for transportation
 - Potential of using pyrolysis liquid in existing power plants
-

Fast pyrolysis liquids can potentially substitute fuel oils. Combustion tests performed using different scale boilers [13–21], internal combustion engines [22–36], and gas-turbine injectors and systems [37–46] have demonstrated that these liquids could be burnt efficiently in standard or modified equipments. These tests have also identified several challenges to pyrolysis liquid use mainly arising from their unusual fuel properties. Important obstacles to commercial applications are variation in liquid fuel quality and lack of product specifications.

The scope of the present paper is to carry out a literature review of the most relevant experience in the field of power generation using biomass fast pyrolysis fuels, identifying results and main findings, technical uncertainties and future R&D work still required.

2. Type of fuels and power generation system (PGS) under investigation

2.1. Fuels

Fast pyrolysis liquids have been produced in the laboratory from numerous biomass sources. Most of the work carried out in larger than laboratory scale has been based on wood derived feeds. High volatile matter (analysed with standard DIN 51720) in wood feedstock corresponds to high liquid yields (Fig. 1) [47]. Increasing ash content (analysed with standard DIN 51719) of feed reduces the organic liquid yield (Fig. 2). Especially potassium and calcium compounds in ash reduce organic liquid yields in fast pyrolysis [48]. Non-wood biomass, often with higher ash contents, has lower organic liquid yields than those reported above for wood feedstocks.

Biomass pyrolysis liquids differ significantly from petroleum-based fuels in both physical properties (Table 2) and chemical composition. Light fuel oil consists mainly of saturated olefinic and aromatic hydrocarbons (C₉–C₂₅) that are immiscible with highly polar pyrolysis liquids [49–51]. Pyrolysis liquids are acidic, unstable, viscous liquids containing solids and a large amount of chemically dissolved water. Heating value, density, and viscosity of pyrolysis liquids vary with water and additives.

As regards the cetane number, a very important parameter which correlates the ignition properties of oil fuels when injected into a diesel engine combustion chamber, the predicted cetane numbers for pyrolysis liquids were evaluated as 13–14 by means of the ignition

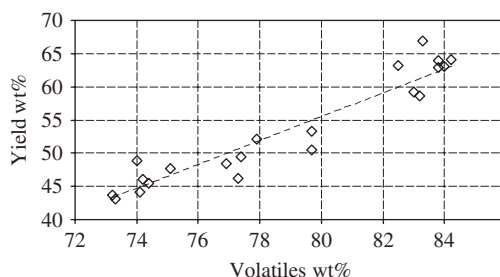


Fig. 1. Yield of organic liquids in wood pyrolysis as a function of feedstock volatile matter (wt% based on dry feed). Average measured yields in PDU operation at 20 kg/h feed during about 50–70 h of operation [47].

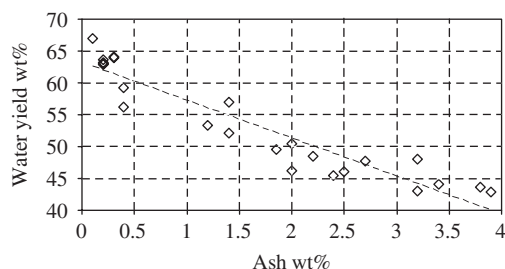


Fig. 2. Yield of organic liquids in wood pyrolysis as a function of feedstock ash. Data from the same experiments as in Fig 1 [47].

quality test (IQT) at CANMET, Canada. Typical cetane number values for diesel oil is 48. The IQT at CANMET is a combustion-based analytical instrument, which allows the determination of the ignition quality of diesel fuels. Test results have demonstrated that the IQT pressure recovery ignition delay is highly correlated with the ASTM D-613 cetane number [54].

The properties of pyrolysis liquids are significantly affected by the kind of biomass used as feedstock (Table 3).

Fast pyrolysis liquids may be classified as:

- Basic pyrolysis liquids
- Solids-free pyrolysis liquids
- Pyrolysis liquids with alcohol addition
- Hot-condensed pyrolysis liquids
- Pyrolysis liquid fractions
- Pyrolysis liquid/mineral oil emulsions.

Basic pyrolysis liquids include homogenous single-phase liquids produced from various biomass sources using different types of fast pyrolysis processes without using any fractionation during or after liquid condensation. The main fuel criteria for these liquids are the homogeneity and even quality of the liquid batch. Water content (measured by

Table 2
Physical properties of pyrolysis liquids and mineral oils [10,12,25,52,53]

Analysis	Pyrolysis liquids	Light fuel oil (Tempera 15)	Heavy fuel oil	JP-4 ^a
Water, wt%	20–30	0.025	0.1	0
Solids, wt%	<0.5	0	0.2–1.0	0
Ash, wt%	<0.2	0.01 ^b	0.03	n.a.
Carbon, wt%	32–48	86.0	85.6	80–83
Hydrogen, wt%	7–8.5	13.6	10.3	10–14
Nitrogen, wt%	<0.4	0.2	0.6	n.a.
Oxygen, wt%	44–60	0	0.6	n.a.
Sulfur, wt%	<0.05	<0.18	2.5	<0.4
Vanadium, ppm	0.5	<0.05	100	<0.6
Sodium, ppm	38	<0.01	20	n.av.
Calcium, ppm	100	n.a.	1	n.av.
Potassium, ppm	220	<0.02	1	<1.5
Chloride, ppm	80	n.a.	3	n.av.
Stability	Unstable	Stable	Stable	Stable
Viscosity, cSt	15–35 at 40 °C	3.0–7.5 at 40 °C	351 at 50 °C	0.88 at 40 °C
Density (15 °C), kg/dm ³	1.10–1.30	0.89	0.94–0.96	0.72 at 20 °C
Flash point, °C	40–110	60	100	–23
Pour point, °C	–10 to –35	–15	+21	<–48
Conradson Carbon Residue wt%	14–23	9	12.2 ^c	n.av.
LHV, MJ/kg	13–18	40.3	40.7	43.2
pH	2–3	Neutral	n.a.	n.av.
Distillability	Not distillable	160–400 °C		95–195 °C

n.a. = Not analysed, n.av. = Not available.

^aKerosene (aviation fuel).

^bAsh contains mainly V and Ni.

^cRamsbottom.

Karl–Fischer titration) of the liquid should not exceed 28 wt% and the variation of the water content of the whole batch is recommended to be within ± 1 wt%. If the water content is very high (above 30 wt%) the liquid separates into two phases of differing properties. Solids content (measured as methanol–dichloromethane, 1:1, insolubles) below 0.5 wt% can be easily obtained using normal cyclone technology.

The quality of pyrolysis liquid can be improved by *solids removal*. The efficiency of cyclones, which remove particles $> 10 \mu\text{m}$, determines the liquid solids content. The solids left may be removed by on-line hot-vapour filtration, or centrifugation/filtration of condensed pyrolysis liquid. The main objective in solids removal is to minimize the loss of organics. NREL [55,56] has successfully removed all solids and most of the ash (Na + K < 120 ppm) by hot-vapour filtration. Organic loss was ca. 10 wt% and the fuel quality of the liquid was improved [57]. No published data on a large-scale demonstration of these methods is available.

Pyrolysis liquid quality may further be improved by *alcohol addition*. Addition of alcohol improves the homogeneity and storage stability [58–60] of the liquid and decreases its viscosity (Fig. 3). Addition of alcohol is beneficial also in solids removal. It dilutes the liquid, reducing its stickiness thus enhancing the filterability of the liquid and minimizing

Table 3
Properties of liquids from different feedstocks produced in pyrolysis units >80 kg/h

Producer reference feedstock	Dynamotive Morris 2000 pine/spruce 100% wood	Dynamotive Morris 2000 pine/spruce 53% wood, 47% bark	Dynamotive Morris 2000 bagasse	Forestera TM VTT data spruce 100% wood	Ensyn VTT data mixed hardwood ^a
Moisture, wt%	2.4	3.5	2.1	6–9	n.av.
Particle size, mm	<1.2	<1.2	<1.2	3–5	n.av.
Ash, wt%	0.42	2.6	2.9	n.av.	n.av.
Bio-Oil					
Water, wt%	23.3	23.4	20.8	23.8	22
Solids, wt%	<0.1	<0.1	<0.1	0.01	0.045
Ash, wt%	<0.02	<0.02	<0.02	<0.001	0.01
Nitrogen, wt%	<0.1	0.3–0.4	0.7	0.04	0.2
Sulphur, wt%	<0.01	<0.05	<0.1	<0.01	<0.01
Viscosity (20 °C), cSt	73	78	57	n.av.	n.av.
Viscosity (40 °C), cSt	n.av.	n.av.	n.av.	15	50 at 50 °C
Viscosity (80 °C), cSt	4.3	4.4	4	n.av.	n.av.
Density (15 °C), kg/dm ³	1.20	1.19	1.20	1.19	1.18
Flash point, °C	n.av.	n.av.	n.av.	38	55
Pour point, °C	n.av.	n.av.	n.av.	n.av.	–25
HHV, MJ/kg	16.6	16.4	15.4	17.6	17
LHV, MJ/kg	n.av.	n.av.	n.av.	16.0	15.5
pH	2.3	2.4	2.6	2.4	2.5
Water insolubles, wt%	25	25	24	21	50

n.av. = Not available.

^aA part of the pyrolysis liquid has been removed for chemicals production hence the lignin content is higher than typical [50].

the organic losses in filtration/centrifugation. The decrease of flash point has to be carefully taken into account when adding ethanol.

Fuel properties may also be improved by applying *hot-condensers* during pyrolysis [11,12]. In this procedure, the temperature of liquid scrubbers is increased to distil off the lightest reactive aldehydes and ketones with some water and acids (loss of organics below 10 wt%). Decrease of flash point may be controlled within acceptable limits with this procedure when alcohol is added. The storage stability of the liquid is simultaneously improved [51].

Pyrolysis liquid fractions are produced e.g. by Pyrovac vacuum pyrolysis process [61,62] where the product is initially condensed in several fractions. Red Arrow Inc. is producing smoke flavour and browning agents by using Ensyn RTP technology and removing the lightest water-soluble fraction of the pyrolysis liquid. The heavier, lignin-rich fraction can be used as fuel.

Emulsions are obtained by homogenization of two or more immiscible liquids and by using one or several additives (surfactants and co-surfactants) that lower the surface energy of the interface on the produced droplets. Emulsification can be considered a means to upgrade PL: most of the properties of the emulsion systems (such as stability, viscosity,

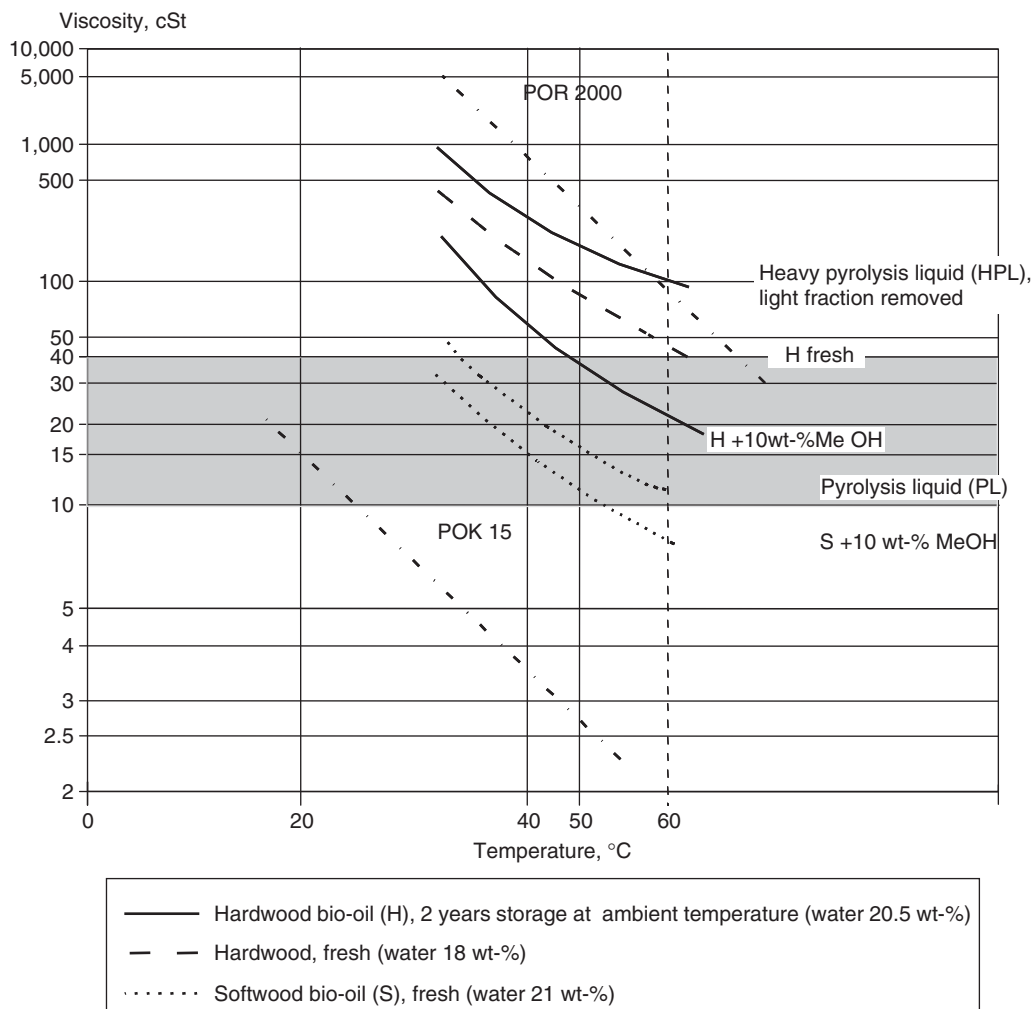


Fig. 3. The effect of solvent addition on the viscosity of biomass pyrolysis oils. The grey area shows a typical viscosity area at engine injection nozzle in heavy (20–40 cSt) and light fuel oil uses (10–20 cSt). POR2000 = heavy fuel oil, POK15 = light fuel oil.

etc.) depend more on the droplet size and size distribution than on the properties of the emulsified fuels. The main aim of emulsion production is to facilitate the use of PL in existing technologies for heat as well as for heat and power generation. Another motivation for the interest in PO-diesel oil emulsions is the improved ignition properties of emulsions compared to pure PL.

Methods of producing stable emulsions of diesel fuel and biomass fast-pyrolysis were investigated by [35,36,63,64]. A large number of commercially available surfactants, as well as ad-hoc developed surfactants were investigated: the amount of additive required for the production of stable emulsion was found in the range of 0.8–1.5 wt%.

2.2. Power generation systems

The liquid fuel obtained from fast pyrolysis of biomass can be used to generate electricity and heat in power generation systems (PGSs). The main power technologies considered in this work are:

- Diesel engines
- Gas turbines
- Co-firing of biomass and coal in large-scale power stations.

While diesel engines and turbines are considered potentially important markets for PL even at rather small generation capacities, co-firing in power stations is confined to large plants.

Stirling engines have also been investigated in combination with PL.

Each energy conversion system has different characteristics, and therefore their adaptation to using PL presents specific problems. Diesel engines, for instance, are based on high pressure and intermittent fuel injection into the combustion chamber, while gas turbines perform continuous fuel combustion even at part load. Residence times are also very different in the two cases. All these energy generation systems require a fine and constant quality fuel atomization in order to achieve efficient combustion and low emissions.

3. Use of biomass pyrolysis liquid for power generation

3.1. Diesel engines

3.1.1. Pure PL in diesel engines

The first work on using pyrolysis liquid in diesel-engines was carried out in Finland by VTT (Technical Research Centre of Finland) and Wärtsilä. Engine performance and emissions were studied in a 4.8 kW single-cylinder test engine [22], in a 60 kWe four-cylinder Valmet 420 DS-engine [24,65], and in a 410 kW Vasa 18V32 engine using one of its 18 cylinders on pyrolysis liquid [25,26]. It was observed that:

- Pilot injection of diesel oil is needed
- Fast heat release of pyrolysis liquid is observed
- Encouraging thermal efficiency of 44.9% is achieved
- Specifications laid down on the properties of the pyrolysis liquid have to limit the solids content to a very low level and must provide tight heating value control
- Water content of pyrolysis liquid evens out the temperature gradient and is beneficial for NO_x reduction
- The high density and low heating value of pyrolysis liquid has to be carefully considered when designing the fuel feeding system
- Severe material wear occurs.

Various pyrolysis liquid qualities and materials were tested in test-rigs at VTT [66] and Wärtsilä [26]. Nozzles lasted longer when using hot-vapour filtered pyrolysis liquid, but it was clear that standard nozzle material would not be adequate for use with pyrolysis liquid

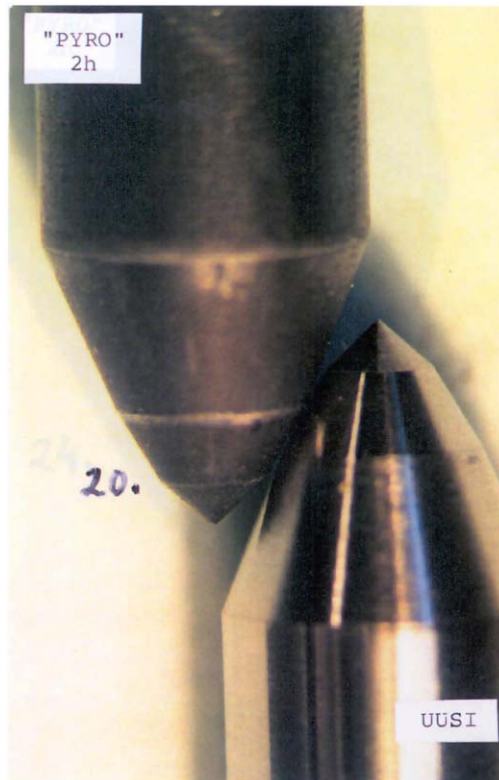


Fig. 4. Injection needle after 2 h running (left) with pyrolysis liquid, and as new (right).

(Fig. 4). The importance of solids removal was emphasized [66]. The most resistant materials [26] in the test-rig conditions were:

- Injection equipment: Martensitic Sintered Stainless steel M390: 1.90% C, 20% Cr, 1% Mo, 4% V, 0.6% W
- Injector holders and bodies: X35CrMo17
- Pushrods and needles: X90CrMoV18 (AISI 440B) stoff 1.4112 martensitic stainless steel with 57 HRC hardness
- Springs: stoff 1.430 Austenitic stainless steels 600–900 N/mm² UTS
- Sealings: EPDM and Teflon O rings
- Copper is suitable for washers.

Wärtsilä evaluated the energy production chain comprising “wood waste → pyrolysis plant → diesel power plant (1.5 MWe engine) → Power for machinery”, and concluded, for example, that wood sawmills would be commercially attractive [26]. The location of a pyrolysis liquid power plant should be close to wood waste sites. A 1.5 MWe medium-speed diesel power plant was modified for pyrolysis liquid use based on the experience gained in the earlier studies. A pyrolysis liquid feeding tank (day tank) and feeding (booster) unit was constructed. The injection rate–injection system had been developed [26]

to 1450 bar and less than 30° injection period (6.7 ms) using the extreme fuel properties of 15 MJ/kg heating value and 1.2 kg/dm³ density. Handling, quality control, feeding, and behaviour of a large amount (100 t) of pyrolysis liquid was studied [67]. Main results were:

- All standard gaskets in the feeding system and seals in pumps could not tolerate the low pH of PL.
- Day/feed tank should be equipped with efficient mixing and temperature control to avoid segregation of PL.
- No direct heating of PL allowed, preheating <90 °C needed for viscosity reduction, minimum PL re-cycling.
- In order to avoid lacquering at pistons or nozzles, the lubricating properties of pyrolysis liquid should be improved and/or the lacquer forming compounds removed from the liquid.
- To prevent problems with the leakage of pyrolysis liquid to the lubricating oil side, a centrifuge in the lubricating oil line should be considered.
- Before carrying out large-scale diesel-engine tests, more R&D on the fuel feeding line and the injection nozzle system in a test-rig was recommended.

Wärtsilä stopped the development work mainly due to poor quality (i.e. high solids content) of pyrolysis liquids of that time.

A detailed investigation on PL use in diesel engines has been carried out by MIT [31,32]. Two different PLs, produced by NREL and ENSYN, were tested. The scope of this work was to investigate the use of PL in a direct injection single-cylinder 4500 rpm Ricardo diesel engine, to understand the ignition delay and heat release rates by means of a combination of experimental activity and numerical modeling of spray, and to explain the observed difference between the behaviour of NREL and ENSYN oils in diesel engine.

Compared to diesel oil nr 2, PLs show significant ignition delay, and air preheating (55 °C) is necessary to achieve reliable ignition. Diesel oil showed greater heat peak release than both PLs: The heat peak release for NREL oil was higher than for ENSYN oil. The combustion behaviour of both PLs was significantly different to diesel oil: they did not show any shift between the premixed phase and the diffusion-controlled phase that is typical of diesel fuel. The heat peak release was always lower and delayed for PLs, compared to diesel [31,32].

An important finding in these investigations was that PL combustion in diesel engines is mainly characterized by slow chemistry (i.e. it is kinetically limited) and not only by the low quality of atomization, while diesel oil combustion is mainly limited by mixing. Another important result was that the ignition delay does not only depend on PL water content. In fact, a significant role is also played by the severity of thermal cracking during the production process. The thermal efficiency of both PLs was equal to that of diesel oil. As far as diesel engine and system adaptation was concerned, several actions were taken, such as fuel return diversion from injector to external tank, in line switching between diesel, installation of 40 µm stainless steel filters in the pump circulation loop (after 10 µm PL pre-filtering), lubricity improver (Lubrizol 9520A, 0.1%v/v) addition and ignition improver addition (di-ethylhexynitrate, 15%v/v) to ethanol when flushing (every 15 min).

Nevertheless, it was not possible to achieve more than 6 h of operation with PL fuel, mainly due to damages to the nozzle and injection systems, buildup of carbon deposits in the combustion chamber and exhaust valve.

In the UK, Ormrod conducted studies [9,29,68] using pyrolysis liquid as fuel in a Blackstone ER6 230 kW 6-cylinder diesel-engine with 1–3 cylinders running on pyrolysis liquid. The aim was to establish optimum operating characteristics, minimum handling requirements, emissions, erosion–corrosion levels, maintenance and costs for a dual fuel diesel engine running on bio-oil (Table 4a and b).

Ormrod reported serious erosion–corrosion problems when using standard materials [9]. Silicon carbide coatings were recommended for future tests. Build up of lacquer on the injector needle and fuel pump plunger causing the latter's seizing was also observed. Compared to diesel oil, NO_x and SO_x were low, CO ten-times higher and CO_2 almost equal. The thermal efficiency when operating on bio-oil with pilot injection was 32.4% (34.3% on diesel). More than 400 h of operation have been accumulated in this dual-fuel engine [10].

3.1.2. Blending, emulsions and mixtures of PL with other fuels in diesel engines

Various authors have investigated the use of PL in combination with standard diesel oil in engines. The following combinations have been reported:

- PL blended with Dyglyme (Diethyl glycol dimethyl ether)
- PL emulsified with diesel oil
- PL blended with diesel oil just before injection.

Tests on blends of PL with dyglyme (Diethylene glycol dimethyl ether, an oxygenated compound) were carried out by Istituto Motori-CNR in Italy [33,34]. Dyglyme has a very high cetane number (112–130), very low sooting tendency, and suitable physical–chemical properties for commercial medium-duty diesel engines: dyglyme is miscible with PL, so it was considered for testing. PL from VTT has been mixed with dyglyme at 15.8, 30, 44.1 and 56.8 wt%, and tested in a small diesel engine (Ruggerini, 11 kw). A higher and slightly earlier heat peak release has been observed compared to pure diesel oil: a steeper rise and a narrower heat peak release were reported. Minor differences were found in the overall combustion process and the evaporative phase in particular. The ignition delay increases with PO amount but, probably because of dyglyme, it is always lower than pure diesel oil (except at 56.8 wt% concentration).

The Istituto Motori research group also tested—in the same engine—emulsions (prepared by CANMET) of diesel oil and VTT and Dynamotive PLs at 30 wt% concentration. A significantly greater heat peak release has been observed for emulsions (approximately 50% greater than pure diesel oil), but this behaviour was more evident with Dynamotive liquid rather than with VTT liquid (thus showing the effect of PL characteristics on heat release). The peak is also slightly shifted ahead compared to diesel oil: the ignition delay is also considerably larger than diesel.

Solid matter deposits were observed on the injector tip using dyglyme blends. Nevertheless it seems that up to 44.1 wt% PL reliable operation can be achieved, even if the rather short-term tests carried out limit this conclusion. In contrast to almost all other references, no engine problems were reported with emulsions.

Emulsions were also investigated by other research teams. Tests on emulsions produced using ENEL, BTG and Dynamotive PL [35,36] resulted in rapid corrosion of injector needles, in both small- and medium-scale engines. Substituting the standard nozzle with a stainless steel one, 5 h continuous operation were achieved in a slow speed diesel engine

Table 4a
Selected experimental research work on pure PL in diesel engines (single or dual-fuel injection)

	[22]	[24,65]	[25,26]	[31,32]	[9]
Stated scope of work	To test the use of pyrolysis oil as a fuel in a diesel-engine	To determine the engine performance and emissions using PL	To test the performance of a commercial diesel-engine with PL. Material testing	To compare ignition delay and combustion behaviour of PL. To compare PL and diesel. To compare different PLs	To establish operating characteristics, emissions, erosion-corrosion, maintenance and costs for a dual fuel diesel engine running on PL
Engine	Petter AVB 0070 test engine, 1 cyl. 500 cm ³ DI, naturally aspirated Bore: 80 mm Stroke: 110 mm Compression ratio: 15.3:1 Maximum power: 4.8 kW BMEP: 5.2	Valmet 420 DS-engine Direct Injection, turbocharged, 4 cylinders Bore: 320 mm Stroke: 120 mm Compression ratio: 16.5:1 Maximum power: 64 kW BMEP: 11.7	Wärtsilä Vasa 18V32 Pilot injection, 18 cylinders, 1 of which was used for PL Bore: 320 mm Compression ratio: 12:1 Rated speed: 750 rpm Maximum power: 410 kW BMEP: 23.1	Ricardo Hydra Mark Direct Injection, 1 cyl., 0.4498 l Bore: 80.26 mm Stroke: 88.9 mm Compression ratio 19.8:1 Natural aspiration Injector: Bosch A, 4 holes × 0.21 mm diam × 155° cone angle Opening pressure: 250 bar	Mirrlees Blackstone Ltd. of Stamford, England, ERDFS6 Engine type: Normally aspirated, single acting, 4-stroke cycle Cylinders: 6 vertical in-line Water cooling Displacement (cm ³): 0.0113 (m ³) × 6 Injector: 6 holes Max rotational speed (rpm): 750 Max power (kW): 41.94 kW/cyl at 750 rpm (56.25 bhp/cyl at 750 rpm) Max power for electrical generation (kW _e): 250 at 750 rpm
Tested fuels	Ensyn RTP PO Static injection timing BTDC: 24 Rated speed: 2000 rpm	Static injection timing BTDC: 17 Rated speed: 1500 rpm Ensyn RTP, straw derived PL	Ensyn RTP, mixed hardwood derived PL Static injection timing BTDC: 17	Diesel No.2 Rated speed 4500 rpm	BTG rotating cone pine PL
Engine adaptations and other actions	Test procedure: <ul style="list-style-type: none">● Pilot injection● Start with diesel fuel in both pilot and main injection system, the main fuel was switched to ethanol, and finally to PL, stopping in reverse order	To avoid dramatic camshaft changes and complete engine reconstruction's the concept using the electronically controlled pressure amplifier system has been developed	NREL M2 10 ENSyn RTP 15TPD PL pre-filtering 10 μm, in-line filtering 40 μm	1–3 cylinders out of 6 running on PL	

Table 4a (continued)

[22]	[24,65]	[25,26]	[31,32]	[9]
			<p>Buildup of carbon deposits in the combustion chamber and exhaust valve</p> <p>Same indicated thermal efficiency as diesel (~36%), lower cyl. pressure rise rates</p> <p>Kinetically controlled PL combustion, mixing controlled diesel</p>	<p>Thermal efficiency on bio-oil with pilot injection 32.4% (34.3% on diesel)</p> <p>Material problems. Silicon carbide coating suggested for future tests</p> <p>Lacquering on injector needle and fuel pump plunger</p> <p>Fuel injection system materials have to be changed or lubricating and flow properties of PL have to be improved</p>
Other	PL filtration test, Corrosion tests, Rig Testing – Nozzle material selection		Spray combustion model	

Table 4b
Selected experimental research work on blended/emulsified PL in diesel engines (single or dual-fuel injection)

	[33,34]	[35,36]
Stated scope of work	To assess PL application in medium-light-duty diesel engines	To investigate PL/Diesel emulsion use in diesel engines of various sizes and capacities
Engine	Ruggerini RP 170 Direct Injection, 1 cyl., 0.747 l Bore: 100 mm Stroke: 95 mm Compression ratio 18:1 Natural aspiration Injector: Bosch P, 4 holes \times 0.28 mm diam \times 160° cone angle Opening pressure: 200 bar Rated Power: 11 kW at 3000 rpm Rated Torque: 44 Nm at 2200 rpm Swirl ratio: 1.8 Comb. chamber d/h ratio: 4.6 Hydrotreated diesel (HDT) PL–diglyme blend PL–diesel No 2 emulsions No air (28 °C) or fuel pre-heating	Ormmrod test (UK): Mirreles Blackstone Ltd. of Stamford, England, ERDFS6 Engine type: normally aspirated, single acting, 4 stroke cycle Cylinders: 6 vertical in-line Water cooling Displacement (cm ³): 0.0113 (m ³) \times 6 Max rotational speed (rpm): 750 Max power (kW): 41.94 kW/cyl at 750 rpm (56.25 bhp/cyl at 750 rpm) Max power for electrical generation (kWe): 250 at 750 rpm Injector: 6 holes
Tested fuels	PL–diglyme blend	PL–diesel oil emulsions (25/75, 50/50, 75/25 w/w%)
Engine adaptations and other actions	Strictly stock engine, no modifications to the engine and to the fuel supply/injection system Fuel injector spill return diverted to external tank Injector dismantled and inspected every run. Pump and whole engine only at the end of the test campaign 30 min Diesel (at warm-up and shut-down)	Modified injector nozzle (stainless steel V4A/671–1.4435) Injector needle in standard material (A Senertech Sachs-HKA H53 DI water cooled engine, 5.3 kW, has also been tested without success at Kassel Univ.)
Flushing	20–30 min diesel warm up phase	Diesel oil

Table 4b (continued)

	[33,34]	[35,36]	
Run	Several hours (typical test duration: 1 h)	53–116 min (depending on test nr)	1–3 h (depending on test nr)
Main results & conclusions	PL–diglyme blends: Max amount of PL: 44.1 wt% successfully tested (56.8 wt% of PL: test lasted only 3 min, then needle seized) Ignition delay increases with PO content PL–Diesel emulsions: Combustion similar to behaviour Diesel. No problems to the injector General result: no major problems to components even after extended operation Specific fuel consumption scaled with fuel LHV Spray visualization	Very fast enlargement of injection channel diameter in the standard nozzle Emission measurements	Similar results to Univ. Florence-Pasquali Reported damages to injector nozzle, tip, needle and fuel pump External Injection test (EIT)
Other			

(by the University of Kassel). After this time the test had to be stopped due to unacceptable deterioration of the injector's needle.

Emulsions were also produced by CANMET [63], and a detailed investigation on the main characteristics of PL/diesel emulsions carried out, but no engine tests were reported.

Finally, very recently PYTEC [69] reported successful operation of a 12-cylinder Mercedes-Benz diesel engine with biomass fast pyrolysis liquid produced in the Finnish ForesteraTM process developed by Fortum. Twelve hours of efficient operation (on an average of 300 kW power, i.e. 3600 kWh electricity generation) have been achieved: a mixture of pyrolysis oil (96 vol%v) and diesel oil (4 vol%) were fed to the 12-cylinder high-pressure single-injection engine. Critical components (e.g. pumps and injector nozzles) were redesigned and their materials carefully selected to allow for the corrosive character of bio-oil. No major problems have been reported.

3.1.2.1. Conclusions on the use of PL in diesel-engines. The work carried out on PL in diesel-engines demonstrates that:

- Fuel oil quality of pyrolysis liquids needs to be improved: no solids, better lubricating properties/removal of lacquering compounds, better thermal stability.
- Standard materials have to be changed at least for injection nozzle, needle bodies, and pressure valves. Gaskets and seals in pumps should tolerate low pH.
- No direct heating of fuel is allowed.
- Short preheating <90 °C (preferably <50 °C).
- Liquid re-cycling has to be limited to prevent fuel quality deterioration.
- Water content evens the temperature gradient and is beneficial for NO_x reduction.
- Water content is not the only factor responsible for the ignition delay, but also the extent of thermal cracking during the production process plays a role.
- The high density and low heating value of pyrolysis liquid necessitates a re-design of the fuel feeding system.
- The upgrading of PL through emulsification improves the fuel characteristics and makes easier its use, but technology/material adaptation is still necessary as regards the most critical components (injector needle and nozzle, injection pump).
- Blending of pure PL with high-cetane oxygenated compounds is another possible and effective upgrading method.

3.2. Gas turbines

Pioneer tests with pyrolysis liquids were carried out by Kasper et al. [70] in a J69-T-29 gas turbine combustor rig at Teledyne CAE (USA) using slow pyrolysis liquids. Moses [71] and Moses and Bernstein [72] concluded that in developing a fuel specification for pyrolysis liquids it is necessary to assure fuel quality and price so that engine development costs can be minimized and satisfactory performances and durability guaranteed. Also Boucher et al. [73,74], investigated pyrolysis oil as a fuel for gas turbines. The major performance and durability parameters in gas turbine application are: ignition, lean stability or turndown ratio, combustion efficiency, liner temperatures, exhaust particulates, exhaust CO, NO_x, and hydrocarbons, corrosion, erosion and deposition, thermal stability, and materials compatibility. Major topics for further study are: the effect of fuel oil

properties and chemical composition of pyrolysis liquids on atomization and performance and durability parameters, soot formation (and hence effects on flame radiation, liner temperature, and particulate emissions), corrosion of turbine blades (due to high alkali content in presence of chlorine), materials (i.e. metal and non-metallic elastomers and seals).

The first industrial development with fast pyrolysis liquids in GT was carried out by Orenda Aerospace (Table 5) in an extensive experimental program [39–42]. The selected turbine was a 2.5 MWe class—GT2500 turbomachine, designed and built by Mashproekt in the Ukraine. The following preliminary actions were taken:

- Fuel heating up to 70 °C, to reduce viscosity
- Ash filtering/alkali content reduction during fuel production
- Material selection compatible with acidity of the biofuel, such as austenitic stainless steel [77]
- Power plant started with standard fossil fuel.

The GT2500 industrial turbine uses diesel oil instead of kerosene, which is the standard fuel for aviation GTs. Unlike aero-derived GTs (using annular combustion chambers), the “silo” type combustion chamber is adopted in many industrial GTs (as the GT2500). It may be modified more easily since this type of combustion chamber provides a ready access to the main components, and dimensions can be modified.

In preliminary atomization tests carried out by Orenda, a wider cone angle was generated by both water and PL, compared to diesel oil, due to lower viscosity and surface tension of diesel and the interaction between primary and secondary flows. PO droplets were found to be twice the size of diesel droplets.

A complete low-pressure PL supply system was designed and built. Both diesel and PL are preheated by hot glycol before being fed to the high-pressure pumps.

The resistance of selected GT components under exposure to hot gases from PL combustion has been verified by atmospheric flame tunnel and furnace exposure testing. The tested components were: liner, collector, first to third stage turbine nozzles and blades. Furnace exposure was performed at 850 °C (liner, collector, first and stage nozzles and blades, second stage nozzles) and 650 °C (remaining parts), that represent the critical temperatures for alkali corrosion. While no significant damages were found after flame tunnel testing, some indications of attack were reported from furnace tests (on first stage nozzles, first stage blades and combustion liner), probably due to the nature of the test which was designed to maximize damage.

The GT combustor and the GT nozzle must be adapted to take into consideration the heating value of the biofuel, which is lower than for diesel oil. The GT CC fuel nozzle was modified [39–42] to allow for a larger fuel flow in the secondary passage in order to compensate for the lower heating value of PO and to maintain the same overall power output. The modified nozzle has three passages instead of two, the third one being added to assist fuel atomization (diesel during ignition, PO during normal operation). The prototype nozzle required diesel preheating to avoid PO temperature fall in this component and high thermal gradients in the nozzle passages.

The hot section was also redesigned [46]: all hot section vanes and blades can now be replaced on site without gas turbine removal. A new on-line hot section cleaning system

Table 5
Selected experimental activities on biomass PO use in GTs (whole plant, GT combustion chamber, injection)

	[39,41]	[43,46]	[75]	[74]	[76]
Stated scope of work	To determine technical feasibility of PO in GT	To determine technical feasibility of PO, EtOH, BioDiesel, bituminous Crude Oil in GT	To demonstrate power generation from PO in GT	To study combustion of PO and mix. with ethanol (80% PO–20% Ethanol by vol., 86.45% PO–13.55 EtOH% by weight) in a standard GT combustor	To characterize sprays of softwood bark pyrolysis oil from commercial Delavan nozzles
Turbine	Orenda Aerospace GT2500	Orenda Aerospace GT2500	To optimize combustion To compare emissions Deutz T 216 micro GT	Tested GT combustor only, scaled for lab investigation	To verify the Rosin—Rammeler model n.a.
Load	Max power 2500 kW	Max power 2500 kW	Single-shaft Single staged radial compressor and turbine design Dual mode operation TIT 850C Max power 75 kW	Part load	Spray investigation only
Tested PO	Idle—part load—full load RTP – wood waste	Full load Dynamotive	BTG—poplar	Union Fenosa	n.a. Vacuum pyrolysis—mix of softwood bark
PO preheating (°C)	75	90	In-line filtered > 20 μm 50	Ensyn RTP 80 (mix PO–EtOH) 115 (PO)	80
Pilot flame Start-up fuel	up to 100% PO	up to 100% PO	Diesel oil Diesel oil	No JP4 (GT CC heating) + spark plug (PO ignition)	n.a. n.a.
Shut-down fuel PO LHV (MJ/kg)	18–19	15–17	Diesel oil 14.1	15.3	n.a. n.a.

Table 5 (continued)

	[39,41]	[43,46]	[75]	[74]	[76]
PO density (kg/m ³)	1.2–2.0 at 20 °C	1.2–1.3 at 15 °C	1175 at 15 °C	1.26 at 20 °C	1188 at 20 °C
PO water content (wt%)	18–22	15–22	26.1	18.2	13.0
PO viscosity (cSt)	58–119 at 40 °C	17–48 at 40 °C	13.5 at 40 °C	297 at 40 °C	23 at 70 °C
PO injection visc. (cSt)	n.a.	n.a.	~12 cSt	<10 cSt	n.a.
PO pH	2.7–2.9	n.a.	2.65	1.95	n.a.
PO surf. tens. (mN/m)	35–36 at 25 °C	n.a.	n.a.	30–34 at 25 °C	24.1 at 70 °C
Atomization testing (Y/N)	Yes	No	No	Yes	Yes
	(water–diesel–PO)				(water–heating oil–PO)
Spray correlation	No	No	No	Yes—SMD not verified	Yes
Development of prototype nozzle	Yes	Yes	No	No	No
Hot corrosion tests	Yes	No	No	No	No
Combustion tests	Yes	Yes	Yes	Yes	No
Po filtration	n.a.	n.a.	<20 μm particles	Inline, 60 μm mesh	10 μm mesh
Emission measurements	Flame tunnel test only	Yes. At full load	At part load	Yes	No

n.a. = not available or not applicable, TIT = Turbine Inlet Temperature.
 Andrews et al. (1997) ranges refer to max and min values for different PO samples.

using crushed nut shells was developed: the need for cleaning these components is a typical requirement when using unconventional fuels in turbomachineries.

As regards materials, typically, 300 series stainless steels are used in conjunction with high density and fluorinated polyethylene for polymeric components [45]. The GT2500 turbine was first successfully tested with up to 20% diesel and 80% PL, and then with 100% PL. A short period of diesel operation before shut down was sufficient to avoid deposition of black PL tars on the nozzle, the liner and the collector; nevertheless, some ash was deposited in certain hot gas components.

Recently, Magellan Aerospace Orenda Corporation also carried out emission tests on its GT 2500 turbine running with DynaMotive [43,46] and Ensyn [46] pyrolysis oils as well as with other alternative fuels, like ethanol, bio-diesel, and bituminous crude oil [46]. The focus of this work was to provide a power generation package with the engine and fuel handling module for commercial operation in the demonstration plant under construction in West Lorne, Ontario, Canada. The commercial gas turbine powered demonstration plant will burn pyrolysis oil from wood-waste to generate electricity and steam for sale to the host site [45]. At full continuous output, the plant is design rated to generate 2500 kW of electric power and about 5400 kg/h process steam at over 80% cogeneration efficiency.

The fuel treatment module [46] consists of two tanks for diesel and bio-oil. The bio-oil tank is equipped with a heater and mixer. Up stream of the high-pressure pumps both fuels are preheated by hot glycol, which in turn is preheated by steam. The preheater is designed to preheat the fuel up to 90 °C [43]. Ethanol is used to wash the fuel system internal piping after operation on biofuel. Specially developed algorithms describing the gas turbine and fuel treatment system logic and closed-loop controls have been utilized by PLC-based control system [46].

The turbine performed very well with all fuels [43,46], at different load conditions and during fuel switching. The turbine stabilized quickly following rapid load increases and decreases. It demonstrated stable operation and an impressive turndown ratio between idle and a maximum measured power output of 2.5 MWe, regardless of the fuel used. The fuel handling system was more than adequate in handling both with diesel and bio-fuels.

Table 6 summarizes the measured continuous emission monitor (CEM) emission data at the maximum turbine load of 2.5 MWe. All emissions data are reported as measured and

Table 6
Normalized emissions of various fuel types at maximum load 2.5 MWe [43,46]

Fuel	GT inlet air/ exhaust gas temp (°C)	Fuel flow (l/h)	Generator electrical power (kW)	nCO ₂ (ppmv)	nCO (ppmv)	nNO _x (ppmv)	nSO ₂ (ppmv)
#2 Diesel oil	-2.8/403	1071	2510	4.2	1	321	7
Biofuel (dynamotive)	2.1/417	1883	2510	4.4	48.7	57.5	2
Biofuel (Ensyn)	-10/420	1800	2650	6	55	60	1
Ethanol	2/415	1800	2510	4.5	3	101	2
BioDiesel	11/444	1200	2550	4.3	4.1	321	1.4
Crude oil blend	5.6/467	1055	2510	4.4	14.8	326	421
Ontario emissions limits				60	189	86	

n—readings normalized to 15% oxygen. Turbomachine rotational speed was about 14000 rpm.

normalized to 15% oxygen, which is the standard way of reporting gaseous emissions from gas turbines. Total operating hours with 100% of biofuel were: Ensyn biofuel—50 h and Dynamotive biofuel—5 h [46].

The use of PL in GTs has also been investigated in Germany since 2001. After preliminary tests in a 300 kWth combustion test facility, tests on a very small-scale Deutz T216 GT (75 kWe nominal) were carried out (Table 5) at the Institute for Energy and Environmental Technology of the Rostock University [75]. It was not possible to operate the standard GT with pure PL. A Dual Mode operation was therefore considered and implemented through feeding the main nozzle with PL and the ignition nozzle with diesel oil. The thermal load in the Dual Fuel mode was 580 kWth, approximately 73% of the thermal load in the standard diesel mode (791 kWth). The ignition nozzle was fed with 354 kWth (diesel, 26 bar), and the main nozzle with 226 kWth (PL, 30–45 bar tested) instead of 437 kWth (diesel, 26 bar): the PL injection pressure was therefore increased by 4 bar compared to diesel oil. PL represented approximately 39% of the total thermal input in the Dual Fuel mode.

During experimental tests fouling occurred: deposits, which could be removed only by mechanical action, were found in the GT combustion chamber and on turbine blades. This is a critical issue for long-term operation. The excess air ratio was increased from 3.3 (diesel mode) to 6 (dual fuel mode) indicating a more difficult combustion: the oxygen content in the exhaust was 17.5%. As regards pollutant emissions, CO and HC emissions were significantly greater in the Dual Fuel mode than in the diesel operation, while NO_x emissions were slightly lower: this result is in an indication of a low-quality combustion. It should also be noted that the temperature at the turbine exit decreased from 600 °C (diesel mode) to 486 °C (dual fuel mode).

A proper understanding of the fuel atomization process is a key element for successful operation of the turbomachinery through the implementation of appropriate modifications to the technology. Tests on GT combustion chambers and spray characterization were carried in Spain and Canada [44,76].

The University of Madrid [44] tested mixtures of PL and ethanol (Table 5) in a GT combustor. PL was initially preheated up to 115 °C to achieve acceptable viscosities (below 10 cSt). The pressure swirl atomizer fed with the Union Fenosa (eucalyptus wood) PL produced a 20° spray cone angle, significantly smaller than the 60° of the design angle. Various reasons might explain this behaviour: higher fuel viscosity, gas formation before the injection, pressure drop increase, the most probable being the first and last ones (the pressure drop was increased from 10 to 15 bar in order to maintain the same fuel flowrate).

As the purpose of this work was to investigate an unmodified GT combustor, which was not possible to operate with pure preheated PL, the analysis was then focused on mixtures of PL and ethanol (80 PL–20 EtOH vol%), which allows for acceptable viscosities (below 10 cSt) at 80 °C. As ethanol dissolves the lignin fraction of PL, in-line filtering did not create problems.

Droplet sauter mean diameter (SMD) in injection was estimated by considering various correlations [78–81], each taking into account different parameters and fuel properties. No experimental verification of these correlations has been reported by the authors.

Both combustion and ignition tests were carried out with the PL–EtOH mixture under equivalent working conditions (by keeping the residence time—kinetic time ratio constant) in a laboratory facility operating at 101,234 Pa (compared to the 323,400 Pa of the standard GT combustor). Ignition tests were performed by spark ignition, after a warm up

phase with standard fossil fuel. Stable combustion was achieved under different operating conditions, but low-frequency instabilities were detected.

The observed CO and NO_x emissions as well as the combustion efficiency and temperature rise were rather similar to JP4 fuel operation: however, the combustion efficiency decreases with the biofuel rate. As the PL flowrate is 2.57 greater than the JP4 flow for the same energy contribution, the primary zone works with a higher fuel/air ratio than the theoretical value, and the fuel/air range corresponding to efficient combustor operation is narrower than with JP4. At full load the temperature increase is 40% lower for biofuel, as expected (T_{\max} equal to 680 K instead of 1141 K for JP4). CO emissions are increased compared to JP4: furthermore, at very low load (48% nominal load) CO emissions become even greater, indicating that the range of efficient operation for the combustor is lower for PL–ethanol mixtures than for JP4 fuel.

One of the most recent experimental investigations on PL injection was carried out at the Université de Laval and CANMET, Canada [76]. The research focused on the analysis of sprays of softwood bark pyrolysis oils in Delavan nozzles. This work, even if not specifically focused on gas turbine applications, represents a significant contribution to the understanding of spray generation from PL, and a verification of the correlations used for droplet size distribution and SMD estimation, which is very important information for GT applications.

Various Delavan nozzles have been investigated (1, 1.5 and 2 USgal/h, A-hollow cone and W-all purpose types; calculated FN: 3.68, 5.52, $7.36 \times 10^{-8} \text{ m}^2$), all having 70° as nominal spray angle. The authors investigated water (at 25, 60 and 80 °C), heating oil (20 and 40 °C) and PL (80 °C) in combination with various nozzles. Droplet size distribution was modelled by the Rosin–Rammler equation, and the SMD through a power law equation: these correlations were experimentally verified. The spray characteristics were investigated by setting up a special facility and using Malvern Master-sizer equipment (2600 series particle sizers). The analysis showed that PL can be atomized using commercially available atomizers resulting in SMD below 50 μm. Thus, even if the SMD from PL is greater than water or heating oil sprays, it is still in the typical and acceptable range for liquid fuels in standard GT combustors. Nevertheless, attention has to be given also to large droplets, whose diameters can be as large as 150 μm.

3.2.1. Conclusions on PL use in GTs

The work carried out on PL in GTs demonstrates that:

- It is possible to use PL in GT combustors. Various PLs have been tested on GT or components, from different technologies or feedstocks.
- Fuel pre-heating (70–90 °C) is necessary to reduce the viscosity (<10 cSt).
- Filtering is necessary to reduce ash and solid contents in the PL (reported 10–60 μm filtering).
- Materials must be selected which are resistant to PL acidity, such as austenitic 300 series stainless steels in conjunction with high density and fluorinated polyethylene for polymeric components.
- Tests have been carried out on 100% PL in modified GTs (2.5 MWe), Dual Fuel mode (diesel + PL) in standard micro GT combustion chambers (75 kWe nominal) and on mixtures of PL and ethanol in a lab-scale GT experimental facility.

- It is necessary to modify the GT combustion chamber according to the PL characteristics. GT using a “silo” type combustion chamber are to be preferred for PL applications, as they can be better adapted.
- Nozzles, in particular, must be adapted for the lower heating value (higher flows) as well as for the higher viscosity of the biofuel. Using standard nozzles to feed PL does not allow for full load, and can generate sprays of unacceptable quality. Unless the nozzle is modified, a considerable power decrease will be observed when using PL.
- The plant should be started and shut down with standard fossil fuel, as this procedure warms up the combustion chamber (facilitating PL ignition) as well as helping to remove fouling and deposits from the surfaces at shutdown.
- Some ash deposits were observed on hot gas components. Other experiments reported fouling, with deposits in the GT combustion chamber and turbine blades: these deposits, which can be only mechanically removed, are probably an indication of insufficient combustion quality (due to various possible reasons, such as insufficient residence time, low-quality atomization, etc.).
- Various authors observed that, compared to diesel oil, PL generates narrower cone angles when sprayed (20° instead of 60° C, pure PL) as expected by theory. However, some authors have reported wider angles, probably due to different atomization systems.
- In some experiments, some PL droplets reached twice the size of diesel droplets. However, it was demonstrated that standard nozzles can generate sprays with SMD below 50 μm, i.e. in the range of liquid fuel GT.
- Various correlations have been studied for droplet size and SMD estimation: the Rosin–Rammler equation has been experimentally verified, and SMD estimated.
- Emissions from a modified GT (GT 2500 Orenda plant) were monitored: CO, NO_x and SO₂ were recorded within the Ontario Emissions limits.
- The modified Orenda GT has performed very well in terms of turndown ratio, fuel switching, load conditions and adaptation to different fuels.
- Long-term testing is needed to identify the nature and cause of deposits and corrosion.

3.3. Co-firing

The use of biomass pyrolysis oils in co-firing with fossil fuels has also been investigated and tested on commercial scale. In particular, the use of this biofuel in large coal and natural gas power station was demonstrated.

The advantages offered by cofiring (or co-combustion) biomass in fossil fuel power plants are well known: among others, higher overall plant efficiencies, reduced investment costs compared to 100% biomass plants, already existing industrial sites (advantages in terms of authorizations and permissions).

PL produced by Red Arrow Products Company by the RTPTM process was cofired in a coal station [82] at the Manitowoc public utilities power station, Wisconsin, a 20 MWe low-sulfur Kentucky coal-fired stocker boiler. A total of 370 h of operation have been accumulated, feeding 5% of thermal input by PL, corresponding to 1 MWe power output generated by PL. The plant was operated without significant problems after cost-effective modification of the boiler to allow for cofiring. No adverse effects were observed on emission levels (sulphur emissions reduced by 5%), maintenance programs or ash handling. Waagenar et al. [83] have also reported of co-firing PL in a coal fired power plant.

Biomass PL from BTG has also recently been fired in a combined cycle natural gas power station in Harculo in the Netherlands [84]. This was the first time PL was co-fired at a power plant scale above 20 MWe. The 251 MWe power plant is equipped with a 90 MWe GE-MS9001B gas turbine (top cycle) and a 161 MWe ABB HC61 steam turbine (bottom cycle). The exhaust gases from the gas turbine were directed to a boiler, which was fed with an additional natural gas input: this particular plant configuration offered the opportunity to replace part of its fossil fuel feed with biomass PL during a 2 day test campaign. PL was fed at a rate of 1.9 t/h (equivalent to 7.9–7.8 MW_{LHV} thermal input) into one of the 12 burners of the boiler, and air-assisted atomized at pressure of approximately 4 bar. Tests lasted ~4 h per day, consuming a total of 15 t of PL. The power output setting of the plant remained unchanged. The oil gun operated well with PL, without the need for gun cooling, and after PL operation it was visually similar to heavy oil operated guns. As far as emissions are concerned, a slight (3 ppm) increase in NO_x emissions was observed (64 ppm NG base emissions), due to the replacement of a nitrogen free fuel (natural gas) with a nitrogen-containing one (PL).

3.4. Other applications of biomass PO for power generation

The use of biomass pyrolysis has been also tested in a FLOX[®] burner coupled with a very small-scale Stirling CHP unit [85]. The FLOX[®] burner (FLOX is the acronym for “FLameless-OXidation”), thanks to a higher residence time of the fuel, is particularly well suited for PL (more efficient carbon burnout). The Stirling engine generates energy in the range of 4–9 kWe and 10–25 kWth using propane fuel. It has been operated for 110 h with PL, generating power and heat in the range of 3.1–6.2 kWe and 8–14 kWth (varying PL flowrate). The test demonstrated that, after adequate preheating of the burner, PL can be successfully used in the system, and that emission levels below German standards for diesel engines in the same power range, can be achieved. However, problems with blocking of the atomizers (agglomerates) and the fuel supply (solids in PL) were reported. Efficiencies were low, probably due to the use of un-preheated combustion air.

4. R&D needs and conclusions

The use of PL for power generation requires standardization and quality improvement of this liquid fuel. The following specifications should be fulfilled, at least for applications in diesel-engine and small boilers (<1 MW):

- Even-quality pyrolysis liquid batches
- No solids in the liquid
- Homogenous liquids. Water content of the liquid below 30 wt%. Single-phase liquid structure
- Good storage stability for at least 6 months. Viscosity increase maximum of 100% in the aging test “24 h–80 °C” (which correlates to the changes occurring during 1 year at room temperature). Possible alcohol addition.

Taking into account the particular properties of biomass fast pyrolysis liquid, PL should be first considered in those PGSs using rather steady injection conditions, such as gas turbine or boilers, and only afterwards in diesel engines, where injection is operated at high

frequency and the fuel is subject to significant and cyclic thermal-shear stresses. Moreover, the use of PL in GT combined cycles would allow for greater efficiencies. On the other hand, diesel engines represent a very mature, widely available and proven technology, which can also be easily downscaled. A large maintenance infrastructure already exists worldwide, which facilitates the operation and servicing of the engine.

In the context of gas turbines, Magellan Orenda has done long-term research with the modified GT 2500 gas-turbine which is the only product in this sector currently available. Other researchers studied the use of PL in GTs without modifying the GT combustion chamber. They represent very useful experiments to improve understanding of the mechanisms involved and to identify critical issues.

The Orenda turbine (a rather small one compared to industrial GTs) has been successfully modified (nozzle re-design, new materials, new fuel feeding systems, on-line hot section cleaning system) to accept biomass fast PL and to achieve low pollutant emissions. The main R&D needs are today related to the demonstration of long-term performance and reliability of the modified GT system, materials and components resistance (combustor, injectors, nozzle and turbine) to hot corrosion and deposits, operating and maintenance costs.

If other types and sizes of GTs are considered in combination with PL, detailed work will have to be carried out to adapt each specific technology to this fuel, as PL in standard GT cannot be used with only minor modifications.

Another important R&D area is represented by Micro Gas Turbines, which have been recently developed to commercial scale and are widely available. These are usually single-stage turbomachines employing a centripetal turbine. Addressing small-scale decentralized power generation would modify the economics of PL-based systems and probably further extend the possibility for cogeneration and market penetration.

The use of pyrolysis liquid in diesel-engines is probably the most technical challenging alternative. Various diesel engines of very different sizes have been tested with pure or derived (mixed, emulsified, etc.) PLs. Fuel oil quality and material issues are the most critical aspects to be addressed, as the typical high frequency of the injection process in diesel engines makes PL use difficult. No long-term demonstration has been achieved so far. All these experimental activities except one reported major problems in injector and pump components.

Ideally, PL should be thermally more stable to tolerate liquid recycling. In addition, the lacquering tendency has to be eliminated. The material of the injection nozzle is probably the most important element for successful and reliable operation, but also the fuel pump must be carefully adapted. The high density and low heating value of PL requires careful re-design of the fuel feeding system.

Referring to emulsions and blending with high-cetane oxygenated compounds, it was found that these solutions improve the ignition properties of the fuel, which burn quite well once ignited. However, the use of emulsions seems to accelerate erosion–corrosion phenomena in high-pressure high-speed components, such as the injector (hole of the nozzles, needle). In both cases (emulsification or blending) a high percentage of PL generate deposits buildup on the injector.

Recent promising developments have been achieved using PL-diesel oil mixtures (not emulsions) in Diesel engines.

Stirling engines could also use biomass PL successfully, but the current stage of development of this technology represents a major obstacle to wider applications.

Table 7
Status of PL-based power generation technologies

	Gas turbine	Diesel engine	Co-firing (NG, coal)	Stirling
Development stage	2500 kWe modified system ready for commercial demonstration No other modified GT plants available	Several engines tested: reliable system not yet developed Various activities ongoing	NG cofiring successfully tested	Short-term testing carried out in a very small unit
Major modifications, critical issues	Nozzles, materials, in-line cleaning system, feeding line	Injector and fuel pump material emissions	Oil gun material, pump and feeding line	Pump and injector
R&D needs	Long-term commercial demonstration Modification of other GT turbomachines Demonstration of combined cycles	Development of: effective/reliable pumping and injections systems; good combustion to avoid deposits on the hot parts (cylinder, piston, injector); materials	Long term commercial demonstration	Reliable small scale Stirling engine to be developed and long-term demonstrated with standard fuels before carrying out further tests on PO
Further developments	Application of PO to MGT	Use of emulsions and blends for ignition, fuel handling and injection improvement	Further PO cost reduction to make NG (first) and coal (secondly) co-firing economically possible	As above

Finally, concerning PL cofiring, no major technical problems exist today. The main obstacle seems to be economical rather than technological, as PL use can be implemented by material modifications and minor technological adaptations to an existing power plant. The supply cost of PO is the critical issue to achieve market penetration: estimates by Wagenaar et al. [83], indicate that PO cost needs to be in the range of 4–6€/GJ to be competitive in NG large power stations. Activities are ongoing in the Herculio NG power station operated by Electrabel using BTG PL produced in a 2 t/h plant in Malaysia. The status of development of these alternatives is summarized in Table 7.

Acknowledgments

The authors wish to acknowledge Piero Baglioni, Massimo Bonini, Iacopo Soldaini, Silvia Milani (CSGI, Univ. of Florence, I), Francesco Martelli, Giovanni Riccio (Dept. of Energetics, Univ. of Florence, I), Kai Sipilä, Mårten Westerholm (VTT, FI), Dietrich Meier (IWC, D), John Brammer (Aston Univ., UK), Patrizio Massoli (CNR, I), Colomba di Blasi (Univ. of Naples, I), Vladimir Lupandin, Frank Button (Orenda, CA), and Andrew Kingston (Dynamotive, CA) for their contributions to this work. We also

acknowledge the European Commission, DG Research, for the support given through the EU project COMBIO (contract ENK5-CT2002-00690).

References

- [1] Spath PL, Mann MK. Biomass power and conventional fossil systems with and without CO₂ sequestration—comparing the energy balance, greenhouse gas emissions and economics. Technical report NREL/TP-510-32575, Golden, CO, USA; 2004.
- [2] Van Loo S, Koppejan J, editors. Handbook of biomass combustion and co-firing. Enschede: Twente University Press; 2002 p. 348.
- [3] Scott DS, Piskorz J, Radlein D. Liquid products from the continuous fast pyrolysis of biomass. *Ind Eng Chem Process Des Dev* 1985;24:581–8.
- [4] Scott DS, Piskorz J, Bergougnou MA, Graham R, Overend RP. The role of temperature in the fast pyrolysis of cellulose and wood. *I&EC Res* 1988;27:8–15.
- [5] Graham RG, Freel BA, Bergougnou MA. The production of pyrolytic liquids, gas and char from wood and cellulose by fast pyrolysis. In: Research in thermochemical biomass conversion. Phoenix, Arizona, 1–6 May 1988. p. 629–41.
- [6] Diebold JP, Evans RJ, Scahill JW. In: Klass DL, editor. Energy from biomass and solid wastes, vol. XIII. Chicago: Institute of Gas Technology; 1990. p. 851–78.
- [7] Kjellström B, editor. A study of a biomass liquefaction test facility. Final report of IEA cooperative project biomass liquefaction test facility. Statens Energiverk R:1, Stockholm, 1985.
- [8] Solantausta Y, McKeough P. A techno-economic evaluation of several direct liquefaction processes bioenergy 84. In: Egneus H, Ellegård A, editors. Biomass conversion, Göteborg, 18–21 June 1984, vol. 3. Amsterdam: Elsevier Applied Science; 1985.
- [9] Bridgwater AV, Toft AJ, Brammer JG. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. *Renew Sustain Energy Rev* 2002;6(3):181–246.
- [10] Czernik S, Bridgwater A. Overview of applications of biomass fast pyrolysis oil. *Energy Fuels* 2004;18:590–8.
- [11] Oasmaa A, Peacocke C, Gust S, Meier D, McLellan R. Norms and standards for pyrolysis liquids. End-user requirements and specifications. *Energy Fuels* 2005;19(5):2155–63.
- [12] Oasmaa A, Sipilä K, Solantausta Y, Kuoppala E. Quality improvement of pyrolysis liquid. Effect of light volatiles on the stability of pyrolysis liquids. *Energy Fuels* 2005; doi:10.1021/ef0400924.
- [13] Shaddix CR, Huey SP, Wornat MJ, Davis KA. Fundamental aspects of combustion of biomass pyrolysis oils. Biomass usage for utility and industrial power, Conference proceedings, Snowbird, UT, 1996.
- [14] Shaddix CR, Huey SP. Combustion characteristics of pyrolysis oils derived from hybrid poplar. In: Developments in thermochemical biomass conversion, 1996.
- [15] Hallgren B. Test report of Metlab Miljö Ab. Skelleftehamn: Metlab Miljö Ab; 1997. 17p (Reg. no. ALL-1668, 1996 02 08-09).
- [16] Shaddix R, Huey S. Combustion characteristics of fast pyrolysis oils derived from hybrid poplar. In: Bridgwater AV, Boocock DGB, editors. Developments in thermo chemical biomass conversion. London, UK: Blackie; 1997. p. 465–80.
- [17] Gust S. Combustion experiences of fast pyrolysis fuel in intermediate size boilers. In: Bridgwater AV, Boocock DGB, editors. Developments in thermochemical biomass conversion, Banff, 20–24 May 1996, vol. 1. London, UK: Blackie Academic & Professional; 1997. p. 481–8.
- [18] Gust S. Combustion of pyrolysis liquids. In: Kaltschmitt M, Bridgwater AV, editors. Biomass gasification and pyrolysis. Newbury, UK: CPL Press; 1997. p. 498–503.
- [19] Oasmaa A, Kytö M, Sipilä K. Pyrolysis liquid combustion tests in an industrial boiler. In: Bridgwater AV, editor. Progress in thermochemical biomass conversion, vol. 2. Oxford: Blackwell Science; 2001. p. 1468–81.
- [20] Kytö M, Martin P, Gust S. Development of combustors for pyrolysis liquids. In: Bridgwater AV, editor. Pyrolysis and gasification of biomass and waste, Strasbourg, France, 30 September–1 October 2002. Newbury, UK: CPL Press; 2003. p. 187–90.
- [21] Gust S, Nieminen JP, Nyrönen T. Forestera (TM)—liquefied wood fuel pilot plant. In: Bridgwater AV, editor. Pyrolysis and gasification of biomass and waste, Strasbourg, France, 30 September–1 October 2002. Newbury, UK: CPL Press; 2003. p. 169–74.
- [22] Solantausta Y, Nylund N-O, Westerholm M, Koljonen T, Oasmaa A. Wood pyrolysis liquid as fuel in a diesel power plant. *Biores Tech* 1993;46(1–2):177–88.

- [23] Solantausta Y, Nylund N-O, Gust S. Use of pyrolysis oil in a test diesel engine to study the feasibility of a diesel power plant concept. *Biomass Bioenergy* 1994;7:297–306.
- [24] Solantausta Y, Nylund N-O, Oasmaa A, Westerholm M, Sipilä K. Preliminary tests with wood-derived pyrolysis liquid as fuel in a stationary diesel engine. In: Biomass pyrolysis liquid properties and combustion meeting, Estes Park, Colorado, USA, 26–28 September 1994. NREL-CP-430-7215, NTIS, Springfield, USA, 1995. p. 355–61.
- [25] Gros S. Pyrolysis liquid as diesel fuel. Wärsilä Diesel International. In: Seminar on power production from biomass II, 27–28 March 1995, Espoo, Finland.
- [26] Jay DC, Rantanen OA, Sipilä KH, Nylund N-O. Wood pyrolysis oil for diesel engines. In: 1995 fall technical conference, Milwaukee, Wisconsin, 24–27 September, 1995. New York: ASME; 1995.
- [27] Sipilä K, Oasmaa A, Arpiainen V, Westerholm M, Solantausta Y, Angher A, Gros S, Nyrönen T, Gust S. Pyrolysis oils for power plants and boilers. Biomass for energy and the environment. In: Chartier P, et al., editors. Ninth European conference on bio energy, vol. 1. Amsterdam: Elsevier; 1996. p. 302–7.
- [28] Suppes GJ, Natarajan VP, Chen Z. Autoignition of select oxygenate fuels in a simulated diesel engine environment. Paper (74 e) presented at AIChE National Meeting, New Orleans, LA, 26 February 1996.
- [29] Leech J. Running a dual fuel engine on pyrolysis oil. In: Kaltschmitt M, Bridgwater A, editors. Biomass gasification and pyrolysis, state of the art and future prospects. Newbury, UK: CPL Press; 1997.
- [30] Shihadeh A. Rural electrification from local resources: biomass pyrolysis oil combustion in a direct injection diesel engine. Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, MA, September 1998.
- [31] Shihadeh A. Diesel engine combustion of biomass pyrolysis oils. *Energy Fuels* 2000;14:260–74.
- [32] Shihadeh A, Hochgreb S. Impact of biomass pyrolysis oil process conditions on ignition delay in compression ignition engines. *Energy Fuels* 2002;16(3):552–61.
- [33] Bertoli C, D'Alessio J, Del Giacomo N, Lazzaro M, Massoli P, Moccia V. Running light-duty DI diesel engines with wood pyrolysis oil. In: SAE international fall fuels and lubricants meeting exposition, Baltimore, Maryland, 16–19 October 2000, SAE paper 2000-01-2975, vol. SP-1565, Alternative fuels 2000, p. 1–7.
- [34] Bertoli C, Calabria R, D'Alessio J, Lazzaro M, Massoli P, Moccia V. Diesel engines fueled by wood pyrolysis oil: feasibility and perspectives. In: Fifth international conference on internal combustion engines, SAE-NA 2001-01-025; 2001. p. 43–50.
- [35] Chiamonti D, Bonini M, Fratini E, Tondi G, Gartner K, Bridgwater AV, Grimm HP, Soldaini I, Webster A, Baglioni P. Development of emulsions from biomass pyrolysis liquid and diesel and their use in engines—Part 1: emulsion production. *Biomass Bioenergy* 2003;25(1):85–99.
- [36] Chiamonti D, Bonini M, Fratini E, Tondi G, Gartner K, Bridgwater AV, Grimm HP, Soldaini I, Webster A, Baglioni P. Development of emulsions from biomass pyrolysis liquid and diesel and their use in engines—Part 2: tests in diesel engines. *Biomass Bioenergy* 2003;25(1):101–11.
- [37] Andrews R, Patnaik PC, Liu Q, Thamburaj R. Firing fast pyrolysis oil in turbines. In: Proceedings of biomass pyrolysis oil, properties and combustion meeting, September 1994, Estes Park, Colorado; 1994. p. 383–91.
- [38] Andrews RG, Patnaik PC, Michniewicz JW, Jankowski LJ, Romanov VI, Lupandin VV, Ravich AV. Feasibility of utilizing a biomass derived fuel for industrial gas turbine applications. American Society of Mechanical Engineers (Paper), 1995.
- [39] Andrews RG, Patnaik PC. Feasibility of utilizing a biomass derived fuel for industrial gas turbine applications. In: Bridgwater AV, Hogan EN, editors. Bio-oil production and utilisation. Newbury, UK: CPL Press; 1996. p. 236–45.
- [40] Andrews R, Fuleki D, Zukowski S, Patnaik P. Results of industrial gas turbine tests using a biomass-derived fuel. In: Overend R, Chornet E, editors. Making a business from biomass in energy, environment, chemicals, fibers, and materials. Proceedings of the third biomass conference of the Americas. Amsterdam: Elsevier Science Ltd.; 1997.
- [41] Andrews RG, Zukowsky S, Patnaik PC. Industrial gas turbine tests using a biomass derived fuel. In: Book of abstracts, International conference gasification and pyrolysis of biomass, Stuttgart, 9–11 April 1997.
- [42] Andrews RG, Zukowski S, Patnaik PC. Feasibility of firing an industrial gas turbine using a biomass derived fuel. In: Bridgwater AV, Boocock DGB, editors. Developments in thermochemical biomass conversion. London, UK: Blackie Academic and Professional Press; 1997. p. 495–506.
- [43] Razbin V, Coyle I. Emissions tests on Magellan Aerospace Orenda Corporation, Ogt 2500 gas turbine, CETC Energy Technology Centre, Ottawa, May 2004, CETC-O-ACT-04-043-1 (CF).
- [44] Lopez Juste G, Salva Monfort JJ. Preliminary test on combustion of wood derived fast pyrolysis oils in a gas turbine combustor. *Biomass Bioenergy* 2000;19:119–28.

- [45] Ashmore C. Biomass based cogen plant rated at 2.5MW and 12,000pph steam. Gas turbine world, August–September 2004.
- [46] Lupandin V, Thamburaj R, Nikolayev A. ASME paper number: GT2005-68488 “Test results of the GT2500 gas turbine engine running on alternative fuels: bio oil, ethanol, bio diesel and heavy oil”. Submitted to ASME TURBO-EXPO-05 Congress in Reno-Tahoe, Nevada, USA, 2005.
- [47] Solantausta Y, Oasmaa A. Mid-term report of COMBIO project NNE5-CT-2001-00604, App 6: Hot filtration of fast pyrolysis vapours, 2004.
- [48] Agblevor F, Besler S, Evans RJ. Inorganic compounds in biomass feedstocks: their role in char formation and effect on the quality of fast pyrolysis oils. In: Biomass pyrolysis liquid properties and combustion meeting, Estes Park, Colorado, USA, 26–28 September 1994. NREL-CP-430-7215, NTIS, Springfield, USA; 1995. p. 355–61.
- [49] Elliott DC. Analysis and upgrading of biomass liquefaction products. Final report, vol. 4. IEA Co-operative project D1 biomass liquefaction test facility project. Richland, Washington: Pacific Northwest Laboratory, 1984. 87p + app.
- [50] Oasmaa A, Leppämäki E, Koponen P, Levander J, Tapola E. Physical characterisation of biomass-based pyrolysis liquids. Application of standard fuel oil analyses. VTT Publication 306. Espoo, Finland: VTT; 1997 46p + appendices 30p.
- [51] Oasmaa A, Kuoppala E. Fast pyrolysis of forestry residue. 3. Storage stability of liquid fuel. Energy Fuels 2003;17(3):1075–84.
- [52] Oasmaa A, Peacocke CA. Guide to physical property characterisation of biomass-derived fast pyrolysis liquids. Espoo, Finland: VTT; 2001 65p + appendices 34p.
- [53] Irwin RJ. Environmental contaminants encyclopedia. Jet Fuel 4 Entry. National Park Service, Fort Collins, Colorado, 1 July 1997. <http://www.nature.nps.gov/hazardssafety/toxic/jet4jp4.pdf>
- [54] Ikura M, et al. JOR3-CT98-0253. Final report, 1998.
- [55] Diebold JP, Scahill JW, Czernik S, Phillips SD, Feik CJ. Progress in the production of hotgas filtered biocrude oil at NREL. In: Bridgwater AV, Hogan EN, editors. Proceedings of the second EU Canada workshop on thermal biomass processing. Newbury: CPL Scientific Information Services Ltd.; 1997. p. 66–81.
- [56] Diebold J, Milne T, Czernik S, Oasmaa A, Bridgwater A, Cuevas A, Gust S, Huffman D, Piskorz J. Proposed specifications for various grades of pyrolysis oils. In: Bridgwater A, Boocock D, editors. Developments in thermochemical biomass conversion, Banff, 20–24 May 1996, vol. 1. London: Blackie Academic & Professional; 1997. p. 433–47.
- [57] Shaddix CR, Hardesty DR. Combustion properties of biomass fast pyrolysis oils: Final project report, SAND99-8238, April 1999.
- [58] Czernik S et al. Review of methods for upgrading biomass-derived fast pyrolysis oils. Fast pyrolysis of biomass: a handbook, vol. 2, 2002.
- [59] Diebold JP. A review of the chemical and physical mechanisms of the storage stability of fast pyrolysis bio-oils. In: Bridgwater AV, editor. Fast pyrolysis of biomass: a handbook, vol. 2. Newbury, UK: CPL Press; 2002 424p.
- [60] Oasmaa A, Kuoppala E, Selin J, Gust S, Solantausta Y. Fast pyrolysis of forestry residues. 4. Quality improvement by solvents. Energy Fuels 2004.
- [61] Roy C. The pyrocyclingTM process: new developments, biomass. A growth opportunity in green energy and value-added products, vol. 2. Amsterdam: Elsevier Science; 1999. p. 1227–8.
- [62] Roy C, Calve L, Lu X, Pakdel H, Amen-Chen C. Wood composite adhesives from softwood bark-derived vacuum pyrolysis oils, biomass. A growth opportunity in green energy and value-added products, vol. 2. Amsterdam: Elsevier Science; 1999. p. 521–26.
- [63] Ikura M, Stanculescu M, Hogan E. Emulsification of pyrolysis derived bio-oil in diesel fuel. Biomass Bioenergy 2003;24:221–32.
- [64] Baglioni P, Chiamonti D, Bonini M, Soldaini I, Tondi G. Bio-crude-oil/diesel oil emulsification: main achievements of the emulsification process and preliminary results of tests on Diesel engine. In: Bridgwater AV, editor. Progress in thermochemical biomass conversion, vol. 2. Oxford: Blackwell Science; 2001. p. 1525–39.
- [65] Solantausta Y, editor. VTT energy, Elkraft Power Company Ltd, Union Electrica Fenosa, NesteOy, CRES. Contract AIR2-CT94-1162, Final report, December 1 1994–30 May 1997.
- [66] Solantausta Y, Niinistö M. Injection tests with two biomass pyrolysis oils. Contract EU AIR2-CT94-1162, December 1996.

- [67] Oasmaa A, Sipilä K. Bio fuel oil for power plants and boilers. Properties and behaviour of pyrolysis liquids. Contract JOR3-CT95-0025. Final report 1996–1998.
- [68] Ormrod D, Webster A. Progress in utilization of bio-oil in diesel engines. *PyNe Newsletter*, vol. 10, 2000. p. 15.
- [69] Meier D, Schoell S. New ablative pyrolyser in operation in Germany. *PyNe Newsletter*, Issue 17, April 2004.
- [70] Kasper JM, Jasas GB, Trauth RL. Use of pyrolysis-derived fuel in a gas turbine engine. ASME paper no. 83-GT-96, 1983.
- [71] Moses C. Fuel-specification considerations for biomass liquids. In: Proceedings of biomass pyrolysis oil, properties and combustion meeting, September 1994, Estes Park, Colorado, 1994. p. 383–91.
- [72] Moses AC, Bernstein H. Impact study on the use of biomass-derived fuels in gas turbines for power generation, NREL/TP-430-6085, January 1994.
- [73] Boucher ME, Chaala A, Pakdel H, Roy C. Bio-oils obtained by vacuum pyrolysis of softwood bark as a liquid fuel for gas turbines. Part II: stability and ageing of bio-oil and its blends with methanol and a pyrolytic aqueous phase. *Biomass Bioenergy* 2000;19:351–61.
- [74] Boucher ME, Chaala A, Roy C. Bio-oils obtained by vacuum pyrolysis of softwood bark as a liquid fuel for gas turbines. Part I: properties of bio-oil and its blends with methanol and a pyrolytic aqueous phase. *Biomass Bioenergy* 2000;19:337–50.
- [75] Strenziok R, Hansen U, Künster H. Combustion of bio-oil in a gas turbine. In: Bridgwater AV, editor. Progress in thermochemical biomass conversion. Oxford: Blackwell Science; 2001. p. 1452–8.
- [76] Garcia-Perez M, Chaala A, Kretschmer D, De Champlain A, Huges P, Roy C. Spray characterization of a softwood bark vacuum pyrolysis oil. In: Bridgwater, editor. Science in thermal and chemical biomass conversion conference, 30 August–2 September 2004, Victoria (BC), Canada.
- [77] Fukeli D. Bio-fuel system material testing. In: *PyNE Pyrolysis Network Newsletter*, vol. 7. 1999. p. 5–6.
- [78] Jasuja AK. Atomization of crude and residual fuel oils. *ASME J Eng Power* 1979;101(2):250–8.
- [79] Kennedy JB. High Weber number SMD correlations for pressure atomizers. ASME Paper 85-GT-37, 1985.
- [80] Lefebvre AH. Gas turbine combustion. New York: Hemisphere Publishing Corporation; 1983.
- [81] Lefebvre AH. Gas atomization and sprays. New York: Hemisphere Publishing Corporation; 1989. p.155–200.
- [82] Sturzl R. The commercial co-firing of RTP bio-oil at the Manitowoc Public Utilities power generation station, available at <http://www.ensyn.com>.
- [83] Wagenaar BM, Venderbosch RH, Prins W, Penninks FWM. Bio-oil as a coal substitute in a 600 MWe Power Station. In: 12th European conference and technology exhibition on biomass for energy, industry and climate protection, 17–21 June 2002, Amsterdam, The Netherlands.
- [84] Wagenaar BM, Gansekoele E, Florijn J, Venderbosch RH, Penninks FWM, Stellingwerf A. Bio-oil as natural gas substitute in a 350 MWe power station, In: Second world conference on biomass for energy, industry and climate protection, 10–14 May 2004, Rome, Italy, 2004.
- [85] Bandi A, Baumgart F. Stirling engine with flox burner fuelled with fast pyrolysis liquid. In: Bridgwater AV, editor. Progress in thermochemical biomass conversion. Oxford: Blackwell Science; 2001. p. 1459–67.