Power generation using fast pyrolysis liquids from biomass

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

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

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### 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.
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
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
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 ±7.1 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 μm, 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 2

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

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Pyrolysis liquids</th>
<th>Light fuel oil (Tempera 15)</th>
<th>Heavy fuel oil</th>
<th>JP-4*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water, wt%</td>
<td>20–30</td>
<td>0.025</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>Solids, wt%</td>
<td>&lt;0.5</td>
<td>0</td>
<td>0.2–1.0</td>
<td>0</td>
</tr>
<tr>
<td>Ash, wt%</td>
<td>&lt;0.2</td>
<td>0.01 b</td>
<td>0.03</td>
<td>n.a.</td>
</tr>
<tr>
<td>Carbon, wt%</td>
<td>32–48</td>
<td>86.0</td>
<td>85.6</td>
<td>80–83</td>
</tr>
<tr>
<td>Hydrogen, wt%</td>
<td>7–8.5</td>
<td>13.6</td>
<td>10.3</td>
<td>10–14</td>
</tr>
<tr>
<td>Nitrogen, wt%</td>
<td>&lt;0.4</td>
<td>0.2</td>
<td>0.6</td>
<td>n.a.</td>
</tr>
<tr>
<td>Oxygen, wt%</td>
<td>44–60</td>
<td>0</td>
<td>0.6</td>
<td>n.a.</td>
</tr>
<tr>
<td>Sulfur, wt%</td>
<td>&lt;0.05</td>
<td>&lt;0.18</td>
<td>2.5</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>Vanadium, ppm</td>
<td>0.5</td>
<td>&lt;0.05</td>
<td>100</td>
<td>&lt;0.6</td>
</tr>
<tr>
<td>Sodium, ppm</td>
<td>38</td>
<td>&lt;0.01</td>
<td>20</td>
<td>n.av.</td>
</tr>
<tr>
<td>Calcium, ppm</td>
<td>100</td>
<td>n.a.</td>
<td>1</td>
<td>n.av.</td>
</tr>
<tr>
<td>Potassium, ppm</td>
<td>220</td>
<td>&lt;0.02</td>
<td>1</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>Chloride, ppm</td>
<td>80</td>
<td>n.a.</td>
<td>3</td>
<td>n.av.</td>
</tr>
<tr>
<td>Stability</td>
<td>Unstable</td>
<td>Stable</td>
<td>Stable</td>
<td></td>
</tr>
<tr>
<td>Viscosity, cSt</td>
<td>15–35 at 40°C</td>
<td>3.0–7.5 at 40°C</td>
<td>351 at 50°C</td>
<td>0.88 at 40°C</td>
</tr>
<tr>
<td>Density (15°C), kg/dm³</td>
<td>1.10–1.30</td>
<td>0.89</td>
<td>0.94–0.96</td>
<td>0.72 at 20°C</td>
</tr>
<tr>
<td>Flash point, °C</td>
<td>40–110</td>
<td>60</td>
<td>100</td>
<td>–23</td>
</tr>
<tr>
<td>Pour point, °C</td>
<td>–10 to –35</td>
<td>–15</td>
<td>+21</td>
<td>&lt;–48</td>
</tr>
<tr>
<td>Conradson Carbon Residue wt%</td>
<td>14–23</td>
<td>9</td>
<td>12.2c</td>
<td>n.av.</td>
</tr>
<tr>
<td>LHV, MJ/kg</td>
<td>13–18</td>
<td>40.3</td>
<td>40.7</td>
<td>43.2</td>
</tr>
<tr>
<td>pH</td>
<td>2–3</td>
<td>Neutral</td>
<td>n.a.</td>
<td>n.av.</td>
</tr>
<tr>
<td>Distillability</td>
<td>Not distillable</td>
<td>160–400°C</td>
<td>95–195°C</td>
<td></td>
</tr>
</tbody>
</table>

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

*Kerosene (aviation fuel).

bAsh contains mainly V and Ni.

cRamsbottom.
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,
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%.

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.
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 NOx 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.
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\textsubscript{x} and SO\textsubscript{x} were low, CO ten-times higher and CO\textsubscript{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)

<table>
<thead>
<tr>
<th>Stated scope of work</th>
<th>[22]</th>
<th>[24,65]</th>
<th>[25,26]</th>
<th>[31,32]</th>
<th>[9]</th>
</tr>
</thead>
<tbody>
<tr>
<td>To test the use of pyrolysis oil as a fuel in a diesel-engine</td>
<td>To determine the engine performance and emissions using PL</td>
<td>To test the performance of a commercial diesel-engine with PL</td>
<td>Material testing</td>
<td>To compare ignition delay and combustion behaviour of PL. To compare PL and diesel. To compare different PLs</td>
<td>To establish operating characteristics, emissions, erosion-corrosion, maintenance and costs for a dual fuel diesel engine running on PL</td>
</tr>
</tbody>
</table>

| Engine | Petter AVB 0070 test engine, 1 cyl. 500 cm³ | Valmet 420 DS-engine | Wärtsilä Vasa 18V32 | Ricardo Hydra Mark | Mirrlees Blackstone Ltd. of Stamford, England, ERDFS6 |
|        | Direct Injection, naturally aspirated, 4 cylinders | Pilot injection, 18 cylinders, 1 of which was used for PL | Direct Injection, 1 cyl., 0.44981 | Engine type: Normally aspirated, single acting, 4-stroke cycle |
|        | Bore: 80 mm Stroke: 110 mm Compression ratio: 15.3:1 | Bore: 320 mm Stroke: 120 mm Compression ratio: 16.5:1 | Bore: 80.26 mm Stroke: 88.9 mm Compression ratio: 19.8:1 | Cylinders: 6 vertical in-line Water cooling |
|        | Maximum power: 4.8 kW BMEP: 5.2 Static injection timing BTDC: 24 Rated speed: 2000 rpm | Maximum power: 64 kW BMEP: 11.7 Static injection timing | Maximum power: 410 kW BMEP: 23.1 Static injection timing BTDC: 17 Rated speed 4500 rpm | Displacement (cm³): 0.0113 (m³) × 6 Injector: 6 holes Max rotational speed (rpm): 750 |
| Tested fuels | Ensyn RTP PO Ensyn RTP, straw derived PL | Rated speed: 1500 rpm Ensyn RTP, mixed hardwood derived PL | Diesel No.2 NREL M2 10 ENSYN RTP 15TPD | BTG rotating cone pine PL |
| Engine adaptations and other actions | Test procedure: 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 | 1–3 cylinders out of 6 running on PL |
- diesel fuel
- ignition-enhanced (5% N-CET) ethanol
- ignition-enhanced pyrolysis oil
- ethanol to clean
- pyrolysis oil, etc.

Moderate air preheating (~55 °C) for fuel ignition
Fuel injector spill return diverted to external tank
Pump overhauling and nozzle replacement every 3 h test
Nitrate-enriched ethanol (~every 15 min, 30 min at shut-down). Lubrication: Lubrizol 9520A additive 0.1 vol%.
Ignition improver: di-ethylhexylnitrate 15 vol%
Max continuous: 6 h Typical: 3 h
Fuel injection problems

Run | 12 min periods | 40 min | 4 h (limited by avail. amount of fuel) | 90 min PL and pilot diesel (7–17 wt%)
--- | --- | --- | --- | ---
Main results and conclusions | Engine performance not stable because injector nozzle became clogged
Ignition improver not as effective with PL as with ethanol
PL hard to ignite, burns readily when the combustion has started. PL would be a suitable main fuel for pilot-injection engines
PL with 5% ignition improver gave similar exhaust performance as conventional diesel fuel and better emission performance than the reference fuel (RF35) with poor ignition quality
PL in principle is a viable main fuel option for a pilot-engine
Rapid combustion of PL
Fairly high CO and HC emissions. An oxidizing catalyst may decrease the emissions
Wear in standard and modified injection equipment
Pilot injection needed
Acceptable emissions
Low solids and tight heating value control to specifications
Fast heat release
Water evens the temperature gradient and is beneficial for NOx reduction
Thermal efficiency of 44.9%
Materials for injection equipment, injector holders and bodies, pushrods and needle, springs, sealings, and washers were chosen

Dual fuel mode

Ethanol
- Ethanol

Methanol
<table>
<thead>
<tr>
<th>Reference</th>
<th>Buildup of carbon deposits in the combustion chamber and exhaust valve</th>
<th>Same indicated thermal efficiency as diesel (~36%), lower cyl. pressure rise rates</th>
<th>Kinetically controlled PL combustion, mixing controlled diesel</th>
<th>Thermal efficiency on bio-oil with pilot injection 32.4% (34.3% on diesel)</th>
<th>Material problems. Silicon carbide coating suggested for future tests. Lacquering on injector needle and fuel pump plunger. Fuel injection system materials have to be changed or lubricating and flow properties of PL have to be improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other</td>
<td>PL filtration test, Corrosion tests, Rig Testing – Nozzle material selection</td>
<td>Spray combustion model</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 4b
Selected experimental research work on blended/emulsified PL in diesel engines (single or duel-fuel injection)

<table>
<thead>
<tr>
<th>[33,34]</th>
<th>[35,36]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stated scope of work</strong></td>
<td>To assess PL application in medium-light-duty diesel engines</td>
</tr>
<tr>
<td><strong>Engine</strong></td>
<td></td>
</tr>
<tr>
<td>Ruggerini RP 170</td>
<td>Univ. Flor./Pasquali test (I): Lombardini 6LD400</td>
</tr>
<tr>
<td>Direct Injection, 1 cyl., 0.747 l</td>
<td>Direct Injection, 1 cyl, 0.395 l</td>
</tr>
<tr>
<td>Bore: 100 mm</td>
<td>Bore: 86 mm</td>
</tr>
<tr>
<td>Stroke: 95 mm</td>
<td>Stroke: 68 mm</td>
</tr>
<tr>
<td>Compression ratio 18:1</td>
<td>Compression ratio 18:1</td>
</tr>
<tr>
<td>Natural aspiration</td>
<td>Natural aspiration</td>
</tr>
<tr>
<td>Injector: Bosch P, 4 holes × 0.28 mm diam × 160° cone angle</td>
<td>Injector: 4 holes × 0.20 mm diam × 150° cone angle</td>
</tr>
<tr>
<td>Opening pressure: 200 bar</td>
<td>Opening pressure: 200 bar</td>
</tr>
<tr>
<td>Rated Power: 11 kW at 3000 rpm</td>
<td>Rated Power: 5.4 kW at 3000 rpm</td>
</tr>
<tr>
<td>Rated Torque: 44 Nm at 2200 rpm</td>
<td>Rated Torque: 19.6 Nm at 2200 rpm</td>
</tr>
<tr>
<td>Swirl ratio: 1.8</td>
<td>Air cooled</td>
</tr>
<tr>
<td>Comb. chamber d/h ratio: 4.6</td>
<td></td>
</tr>
<tr>
<td>Tested fuels</td>
<td>Hydrotreated diesel (HDT) PL–diesel blend</td>
</tr>
<tr>
<td>Engine adaptations and other actions</td>
<td></td>
</tr>
<tr>
<td>No air (28°C) or fuel pre-heating</td>
<td>Fuel cooling after spill return</td>
</tr>
<tr>
<td>Strictly stock engine, no modifications to the engine and to the fuel supply/injection system</td>
<td>Surface treatment of injector needle</td>
</tr>
<tr>
<td>Fuel injector spill return diverted to external tank</td>
<td>Water jacket on injector tip</td>
</tr>
<tr>
<td>Flushing</td>
<td></td>
</tr>
<tr>
<td>30 min Diesel (at warm-up and shut-down)</td>
<td>20–30 min diesel warm up phase</td>
</tr>
<tr>
<td>Diesel oil</td>
<td></td>
</tr>
</tbody>
</table>

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### Table 4b (continued)

<table>
<thead>
<tr>
<th>Run</th>
<th>[33,34]</th>
<th>[35,36]</th>
<th>[35,36]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main results &amp; conclusions</td>
<td>Several hours (typical test duration: 1 h)</td>
<td>53–116 min (depending on test nr)</td>
<td>1–3 h (depending on test nr)</td>
</tr>
<tr>
<td>PL–diglyme blends:</td>
<td>Very fast enlargement of injection channel diameter in the standard nozzle</td>
<td>Similar results to Univ. Florence-Pasquali</td>
<td>Max continuous: 5 h</td>
</tr>
<tr>
<td></td>
<td>Max amount of PL: 44.1 wt% successfully tested (56.8 wt% of PL: test lasted only 3 min, then needle seized)</td>
<td></td>
<td>Significantly improved operation in the slow speed pre-chamber engine by using stainless steel corrosion resistant materials for injector nozzle. Tests interrupted due to damaged needle (made of standard material)</td>
</tr>
<tr>
<td>Ignition delay increases with PO content</td>
<td></td>
<td>Reported damages to injector nozzle, tip, needle and fuel pump</td>
<td></td>
</tr>
<tr>
<td>PL–Diesel emulsions:</td>
<td>Combustion similar to behaviour Diesel. No problems to the injector</td>
<td>General result: no major problems to components even after extended operation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific fuel consumption scaled with fuel LHV</td>
<td></td>
<td>External Injection test (EIT)</td>
</tr>
<tr>
<td>Other</td>
<td>Spray visualization</td>
<td>Emission measurements</td>
<td>—</td>
</tr>
</tbody>
</table>
(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 Forestera™ 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 $<90^\circ C$ (preferably $<50^\circ C$).
- 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)

<table>
<thead>
<tr>
<th>Stated scope of work</th>
<th>[39,41]</th>
<th>[43,46]</th>
<th>[75]</th>
<th>[74]</th>
<th>[76]</th>
</tr>
</thead>
<tbody>
<tr>
<td>To determine technical feasibility of PO in GT</td>
<td>To determine technical feasibility of PO, EtOH, BioDiesel, bituminous Crude Oil in GT</td>
<td>To demonstrate power generation from PO in GT</td>
<td>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</td>
<td>To characterize sprays of softwood bark pyrolys ts oil from commercial Delavan nozzles</td>
<td></td>
</tr>
<tr>
<td>To assess emissions</td>
<td>To optimize combustion</td>
<td>To verify the Rosin—Rammler model</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Turbine

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Orenda Aerospace GT2500</th>
<th>Orenda Aerospace GT2500</th>
<th>Deutz T 216 micro GT</th>
<th>Tested GT combustor only, scaled for lab investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max power 2500 kW</td>
<td>Max power 2500 kW</td>
<td>Single-stage radial compressor and turbine design</td>
<td>Single shaft, single staged radial compressor and turbine design</td>
<td>Spray investigation only</td>
</tr>
</tbody>
</table>

Load

<table>
<thead>
<tr>
<th>Load</th>
<th>Idle—part load—full load</th>
<th>Full load</th>
<th>Part load</th>
<th>Part load</th>
<th>n.a.</th>
</tr>
</thead>
</table>

Tested PO

<table>
<thead>
<tr>
<th>Tested PO</th>
<th>RTP – wood waste</th>
<th>Dynamotive</th>
<th>BTG—poplar</th>
<th>Union Fenosa</th>
<th>Vacuum pyrolys is—mix of softwood bark</th>
</tr>
</thead>
</table>

PO preheating (°C)

<table>
<thead>
<tr>
<th>PO preheating (°C)</th>
<th>75</th>
<th>90</th>
</tr>
</thead>
</table>

Pilot flame

<table>
<thead>
<tr>
<th>Pilot flame</th>
<th>up to 100% PO</th>
<th>up to 100% PO</th>
</tr>
</thead>
</table>

Start-up fuel

<table>
<thead>
<tr>
<th>Start-up fuel</th>
<th>Diesel oil</th>
<th>Diesel oil</th>
</tr>
</thead>
</table>

Shut-down fuel

<table>
<thead>
<tr>
<th>Shut-down fuel</th>
<th>Diesel oil</th>
<th>n.a.</th>
</tr>
</thead>
</table>

PO LHV (MJ/kg)

| PO LHV (MJ/kg) | 18–19 | 15–17 | 14.1 | 15.3 | n.a. |
Table 5 (continued)

<table>
<thead>
<tr>
<th></th>
<th>[39,41]</th>
<th>[43,46]</th>
<th>[75]</th>
<th>[74]</th>
<th>[76]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO density (kg/m³)</td>
<td>1.2–2.0 at 20 °C</td>
<td>1.2–1.3 at 15 °C</td>
<td>1175 at 15 °C</td>
<td>1.26 at 20 °C</td>
<td>1188 at 20 °C</td>
</tr>
<tr>
<td>PO water content (wt%)</td>
<td>18–22</td>
<td>15–22</td>
<td>26.1</td>
<td>18.2</td>
<td>13.0</td>
</tr>
<tr>
<td>PO viscosity (cSt)</td>
<td>58–119 at 40 °C</td>
<td>17–48 at 40 °C</td>
<td>13.5 at 40 °C</td>
<td>297 at 40 °C</td>
<td>23 at 70 °C</td>
</tr>
<tr>
<td>PO injection visc. (cSt)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>~12 cSt</td>
<td>&lt;10 cSt</td>
<td>n.a.</td>
</tr>
<tr>
<td>PO pH</td>
<td>2.7–2.9</td>
<td>n.a.</td>
<td>2.65</td>
<td>1.95</td>
<td>n.a.</td>
</tr>
<tr>
<td>PO surf. tens. (mN/m)</td>
<td>35–36 at 25 °C</td>
<td>n.a.</td>
<td>n.a.</td>
<td>30–34 at 25 °C</td>
<td>24.1 at 70 °C</td>
</tr>
<tr>
<td>Atomization testing (Y/N)</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes—SMD not verified</td>
<td>Yes</td>
</tr>
<tr>
<td>(water–diesel–PO)</td>
<td></td>
<td></td>
<td></td>
<td>(water–heating oil–PO)</td>
<td></td>
</tr>
<tr>
<td>Spray correlation</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes—SMD not verified</td>
<td>Yes</td>
</tr>
<tr>
<td>Development of</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>prototype nozzle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot corrosion tests</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Combustion tests</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Po filtration</td>
<td>n.a.</td>
<td>n.a.</td>
<td>&lt;20 µm particles</td>
<td>Inline, 60 µm mesh</td>
<td>10 µm mesh</td>
</tr>
<tr>
<td>Emission measurements</td>
<td>Flame tunnel test only</td>
<td>Yes. At full load</td>
<td>At part load</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Fuel</th>
<th>GT inlet air/exhaust gas temp (°C)</th>
<th>Fuel flow (l/h)</th>
<th>Generator electrical power (kW)</th>
<th>(n)CO(_2) (ppmv)</th>
<th>(n)CO (ppmv)</th>
<th>(n)NO(_x) (ppmv)</th>
<th>(n)SO(_2) (ppmv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2 Diesel oil</td>
<td>-2.8/403</td>
<td>1071</td>
<td>2510</td>
<td>4.2</td>
<td>1</td>
<td>321</td>
<td>7</td>
</tr>
<tr>
<td>Biofuel (dynamotive)</td>
<td>2.1/417</td>
<td>1883</td>
<td>2510</td>
<td>4.4</td>
<td>48.7</td>
<td>57.5</td>
<td>2</td>
</tr>
<tr>
<td>Biofuel (Ensyn)</td>
<td>-10/420</td>
<td>1800</td>
<td>2650</td>
<td>6</td>
<td>55</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>Ethanol</td>
<td>2/415</td>
<td>1800</td>
<td>2510</td>
<td>4.5</td>
<td>3</td>
<td>101</td>
<td>2</td>
</tr>
<tr>
<td>BioDiesel</td>
<td>11/444</td>
<td>1200</td>
<td>2550</td>
<td>4.3</td>
<td>4.1</td>
<td>321</td>
<td>1.4</td>
</tr>
<tr>
<td>Crude oil blend</td>
<td>5.6/467</td>
<td>1055</td>
<td>2510</td>
<td>4.4</td>
<td>14.8</td>
<td>326</td>
<td>421</td>
</tr>
<tr>
<td>Ontario emissions limits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(n\)—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 NOx 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 (\(T_{\text{max}}\) 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 \(\mu\text{m}\). 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 \(\mu\text{m}\).

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 \(\mu\text{m}\) 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° at 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, NOx 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 RTP™ 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\textsubscript{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\textsuperscript{®} burner coupled with a very small-scale Stirling CHP unit [85]. The FLOX\textsuperscript{®} 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.
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 Harculo 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.

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<th>Table 7: Status of PL-based power generation technologies</th>
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<tr>
<td>Development stage</td>
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<tr>
<td>2500 kWe modified system ready for commercial demonstration</td>
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<tr>
<td>No other modified GT plants available</td>
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<tr>
<td>R&amp;D needs</td>
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<tr>
<td>Modification of other GT turbomachines</td>
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<td>Demonstration of combined cycles</td>
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<td>Further developments</td>
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