



THE USE OF BIOMASS DERIVED FAST PYROLYSIS LIQUIDS IN POWER GENERATION: ENGINES AND TURBINES

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by

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Abstract

Power production from biomass derived pyrolysis liquids has been under development for over 15 years. If technically successful, it would make decentralised bio-energy production possible. Several technologies and system components have been developed by academia, R&D organisations, and industrial companies in many countries. Considerable experience has been gained and many useful results published, however there is still a lack of long term operational experience. The present work aims at reviewing the most significant experience in power generation from biomass liquids produced by fast pyrolysis processes and providing some cost data on their use in diesel engines. Power plant technologies addressed are: diesel engines, gas turbines, and natural gas/steam power plants and the main results are reviewed with further R&D needs identified. 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 and further development in this area is required.

1. Introduction

Power produced from biomass has been assessed as one of the leading candidates for reducing CO₂-emissions in power production [1 and 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 across Europe. 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, but at a much lower number and capacity. However there are several advantages to de-coupling solid fuel handling from the actual power generating plant:

- Generation of pyrolysis liquid is the lowest cost liquid biofuel [on an energy basis to bio-ethanol, bio-butanol, etc.],
- CO₂ emission [kg CO₂/kWh] on a life cycle assessment basis is extremely low [< 50 g CO₂/kWh compared to 900-1100 g CO₂/kWh for coal] or if the char is sequestered, negative [25% net CO₂ reduction for slow pyrolysis if all char sequestered [3].
- Possibility of utilisation in small-scale power generation systems as well as use in large power stations (co-firing).
- Possibility to de-couple solid biofuel handling from utilisation (reduced capital and operation costs in utilisation)
- Storability and transportability of liquid fuels - energy density 2-8 times that of the original biomass.
- High-energy density compared to atmospheric biomass gasification "producer gas" or pyrolysis "syngas".
- Intermittent operation feasible - power production at peak times for optimal electricity prices.
- If light fuel oil is replaced, middle distillates are released to be used for transportation

Fast pyrolysis, in which an effort is made to maximise 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, however during fast pyrolysis water is always produced [dehydration of the cellulose polymer], the overall liquid yield from dry wood is typically 75 wt% [dry wood basis]. 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 [4, 5, 6 and 7]. Since then, the technology has been assessed as a promising renewable liquid fuel alternative [8, 9 and 10]. However, several uncertainties remain related to both production and utilisation technology. Comprehensive reviews of pyrolysis oil applications have been recently published by Czernik and Bridgwater [11] and Oasmaa et al. [12] and [13]. Economic uncertainties concerning the competitiveness of the technology remain as long as no commercial fast pyrolysis power plants with an extensive operational record are in operation.

Fast pyrolysis liquids can potentially substitute fuel oils. Combustion tests performed using different scale boilers [14, 15, 16, 17, 18, 19, 20, 21 and 22], internal combustion engines [23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36 and 37], and gas-turbine injectors and systems [38, 39, 40, 41, 42, 43, 44, 45, 46 and 47] 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 primarily variation in liquid fuel quality [viscosity, phase separation, particulates] and lack of international fuel specifications for pyrolysis liquids.

The scope of the present paper is to review 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 clean, wood derived feeds. High volatile matter (analysed with standard DIN 51720) in wood feedstock corresponds to high liquid yields (see Fig. 1) [48]. Increasing ash content (analysed with standard DIN 51719) of feed reduces the organic liquid yield (Fig. 2). Alkali metals, such as potassium, sodium and calcium compounds in ash reduce organic liquid yields in fast pyrolysis [49]. Non-wood biomass types (grasses, straws, etc.), often with higher ash contents, have lower organic liquid yields than those reported above for wood feedstocks.

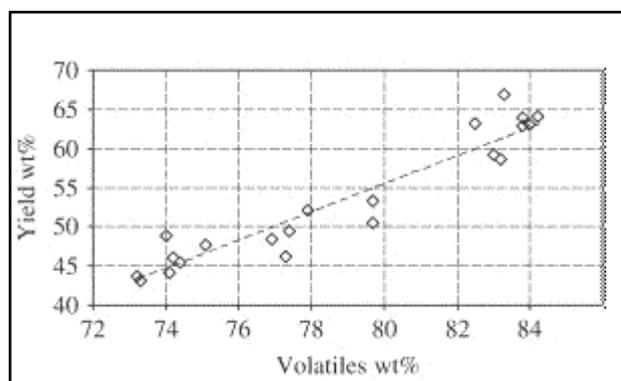


Figure 1.

Yield of organic liquids in wood pyrolysis as a function of feedstock volatile matter (wt% based on dry feed) [48].

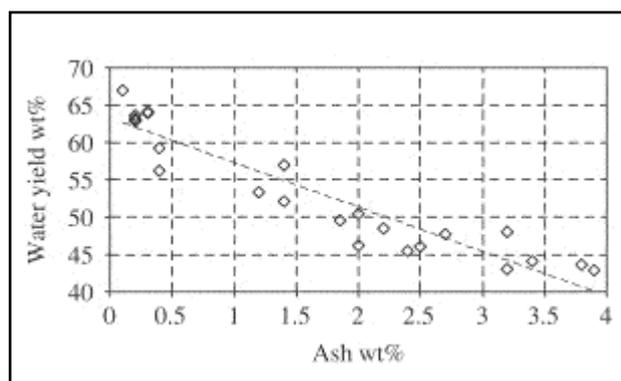


Figure 2.

Yield of organic liquids in wood pyrolysis as a function of feedstock ash. Data from the same experiments as in Fig 1 [48]

Biomass pyrolysis liquids differ significantly from petroleum-based fuels in both physical properties (Table 1) and chemical composition. Light fuel oil consists mainly of saturated olefinic and aromatic hydrocarbons (C₉-C₂₅) that are immiscible with

highly polar pyrolysis liquids [50, 51 and 52]. 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. A typical cetane number 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 [53]. The properties of pyrolysis liquids are significantly affected by the kind of biomass used as feedstock (Table 2).

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 uniform quality (single phase preferred) 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 ± 1 wt%. If the water content is very high (above 30 wt%) the liquid can separate into two phases of differing properties, depending on the production technology. Solids content (measured as methanol-dichloromethane, 1:1, insolubles) below 0.5 wt% can be easily obtained using normal cyclone technology to remove particulates from the hot pyrolysis products prior to liquids recovery.

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 minimise the loss of organics. NREL [56 and 57] has

Table 1. Physical properties of pyrolysis liquids and mineral oils [11, 13, 26, 54 and 55]

Analysis	Pyrolysis liquids	Light fuel oil (Temp era 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.
Sulphur, 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.

^b Ash contains mainly V and Ni.

^a Kerosene (aviation fuel).

^c Ramsbottom.

successfully removed all solids and most of the ash (Na+K <120 ppm) by hot-vapour filtration. Organic loss was around 10 wt% and the fuel quality of the liquid was improved [58].

Recent work by Aston University has also shown that a stable, low solids liquid of 0.006 wt% of the liquid can be achieved by hot gas filtration [59]. No published data on a large-scale demonstration of hot gas filtration have been carried out.

Pyrolysis liquid quality may further be improved by *alcohol addition*. Addition of alcohol improves the homogeneity and storage stability [60, 61 and 62] [58], [59] and [60] of the liquid and decreases its viscosity (Fig. 3). Addition of alcohol is beneficial also in solids removal, causing the lignin polymeric fragments which are chemically bonded to the char to be removed, which normally causes "gelling" when the liquids are filtered at pressure. It also dilutes the liquid, reducing its "stickiness" thus enhancing the filterability of the liquid and minimising 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 [12 and 13]. 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 [52].

Pyrolysis liquid fractions are produced e.g. by Pyrovac vacuum pyrolysis process [63 and 64] 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 homogenisation 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

Table 2.
Properties of liquids from different feedstocks produced in pyrolysis units >80 kg/h

Producer reference feed stock	Dynamotive Morris 2000 pine/spruce 100%wood	Dynamotive Morris 2000 pine/spruce 53% wood, 47%bark	Dynamotive Morris 2000 bagasse	Forestera™ 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.

^a A part of the pyrolysis liquid has been removed for chemicals production hence the lignin content is higher than typical [51].

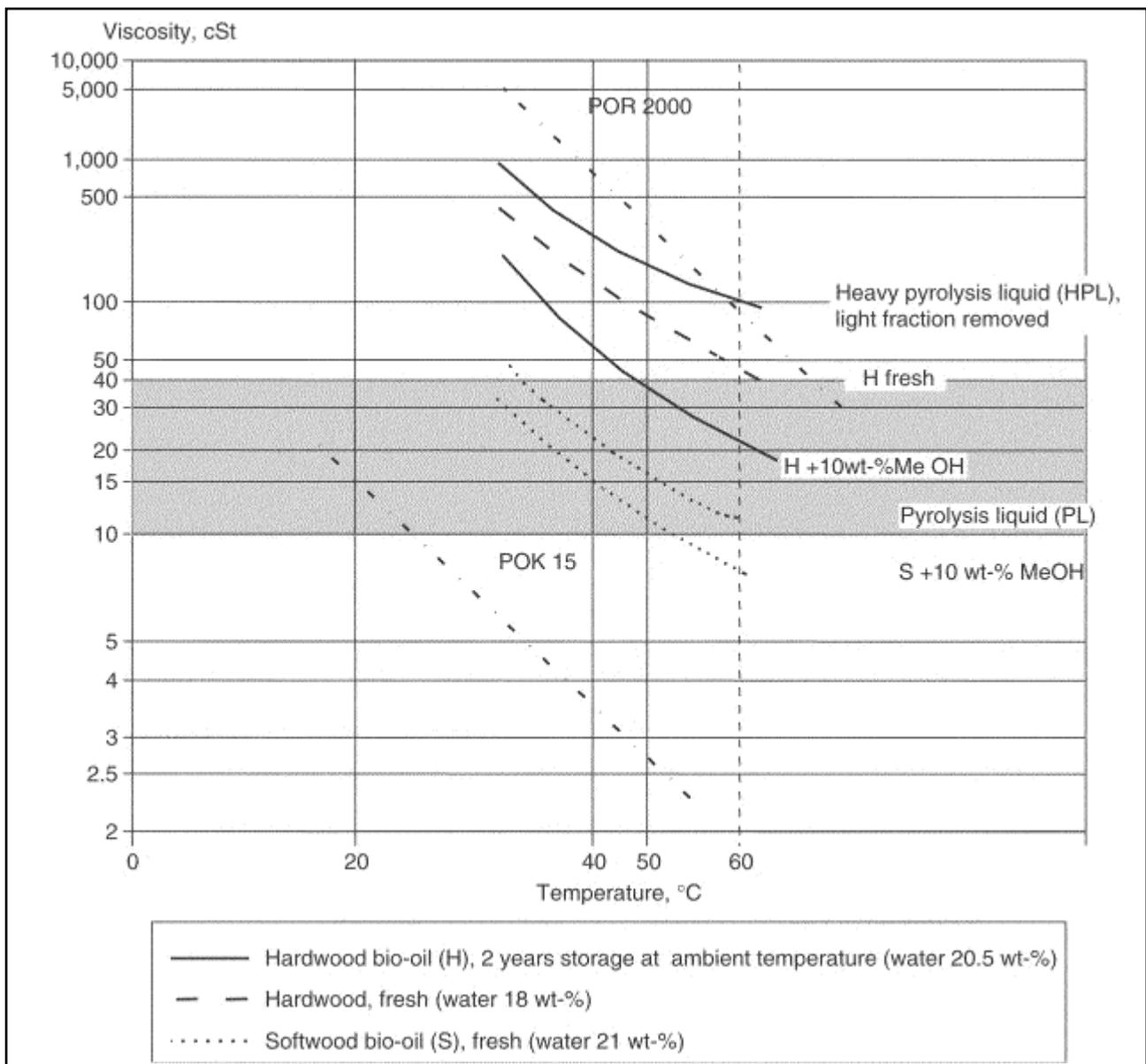


Figure 3.

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.

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 have been investigated by [36, 37, 65 and 66]. 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%. The true cost of modified PL with emulsifiers needs to be fully assessed.

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 atomisation 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 [23], in a 60 kWe four-cylinder Valmet 420 DS-engine [25, 67] and in a 410 kW Vasa 18V32 engine using one of its 18 cylinders on pyrolysis liquid [26 and 27]. 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% was 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 [68] and Wärtsilä [27]. 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). The importance of solids removal was emphasised [68]. The most resistant materials [27] 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 and concluded, for example, that wood sawmills would be commercially attractive [27]. 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 [27] to 1,450 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 [69]. 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 the commercially available pyrolysis liquids of that time.

A detailed investigation on PL use in diesel engines has been carried out by MIT [32 and 33]. 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 4,500 rpm Ricardo diesel engine, to understand the ignition delay and heat release rates by means of a combination of experimental activity and numerical modelling of spray, and to explain the observed difference between the behaviour of NREL and ENSYN oils in diesel engine.

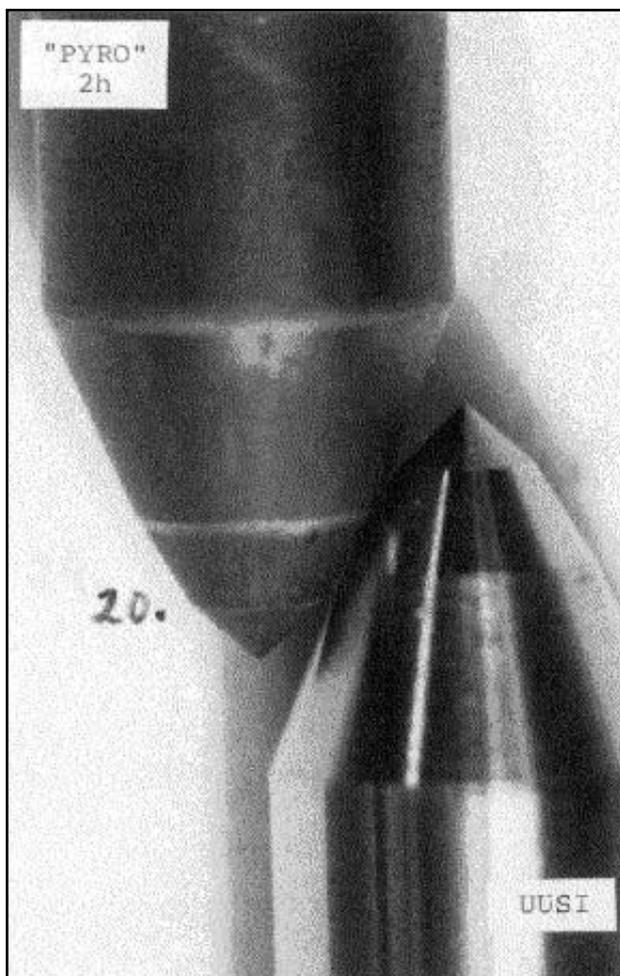


Figure 4.

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

Compared to diesel oil No. 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 [32 and 33].

An important finding in these investigations was that PL combustion in diesel engines is mainly characterised by "slow" chemistry (i.e. it is kinetically limited) and not only by the low quality of atomisation, 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. It would appear that a significant role is also played by the severity of thermal cracking during the liquid 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).

Despite these modifications, 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, build-up of carbon deposits in the combustion chamber and exhaust valve. In the UK, Ormrod conducted studies [10, 30 and 70] 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 3a and Table 3b).

Ormrod reported serious erosion-corrosion problems when using standard materials [10]. 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 CO₂ 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 [11].

Table 3a. Selected experimental research work on pure PL in diesel engines (single or dual-fuel injection)

	[23]	[25,67]	[26,27]	[32,33]	[10]
Stated scope of work	To test the use of pyrolysis oil as a fuel in a diesel-engine	To determine the performance and emissions using PL	To test the performance of 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
Tested fuels	Ensyn RTP PO	Ensyn RTP, straw derived PL	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:	<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	PL pre-filtering 10 µm, in-line filtering 40 µm	1-3 cylinders out of 6 running on PL

Table 3a. continued

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

	[23]	[25,67]	[26,27]	[32,33]	[10]
	<ul style="list-style-type: none"> ● diesel fuel ● ignition-enhanced (5% N-CET) ethanol ● ignition-enhanced pyrolysis oil ● ethanol to clean ● pyrolysis oil, etc. 				
Flushing	Ethanol	Ethanol			<p>Moderate air preheating (approx 55°C) for fuel ignition</p> <p>Fuel injector spill return diverted to external tank</p> <p>Pump overhauling and nozzle replacement every 3 h test</p> <p>Nitrate-enriched ethanol</p> <p>Methanol (every 15 min, 30 min at shut-down). Lubrication: Lubrizol 9520A additive 0.1 vol%.</p> <p>Ignition improver: diethylhexylnitrate 15 vol%</p>
Run	12 min periods	40 min	4 h (limited by avail. amount of fuel)	6 h	90 min PL and pilot diesel (7-17 wt%)
Main results and conclusions	<ul style="list-style-type: none"> ● 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 	<ul style="list-style-type: none"> ● PL in principle is a viable main fuel option for a pilot-engine ● Rapid combustion of PL ● Fairly high CO and HC emissions. An oxidising catalyst may decrease the emissions ● Wear in standard and modified injection equipment 	<ul style="list-style-type: none"> ● 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, 	<ul style="list-style-type: none"> ● Fuel injection problems 	<p>Compared to diesel oil NOx and SOx were low, CO 10 times higher, CO2 almost equal</p>

Table 3a. continued

Selected experimental research work on pure PL in diesel engines (single or dual-fuel Injection)

	[23]	[25,67]	[26,27]	[32,33]	[10]
Main results and conclusions continued	<p>● 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</p>		<p>springs, sealings, and washers were chosen</p>	<p>Buildup of carbon deposits in the combustion chamber and exhaust valve Same indicated thermal efficiency as diesel (36%), lower cyl. pressure rise rates 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 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 3b.

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

[34, 35]

[36, 37]

Stated scope of work	To investigate PL/Diesel emulsion use in diesel engines of various sizes and capacities
Engine	Univ. Flor./Pasquali test (I); Lombardini 6LD400
Engine	Ormrod test (UK); Mirreles Blackstone Ltd. of Stamford, England, ERDFS6
Engine	Univ. Kassel test (D); P.M. Diesel Ltd (India) FM II
Engine	Engine type: normally aspirated, single acting, 4 stroke cycle
Engine	Engine type: vertical pre-chamber
Engine	Cylinders: 1
Engine	Cylinders: 6 vertical in-line
Engine	Water cooling
Engine	Compression ratio 17:1
Engine	Displacement (cm3): 0.0113 (m3)×6
Engine	Water cooling
Engine	Max rotational speed (rpm): 750
Engine	Displacement (cm3): 1432
Engine	Max rotational speed (rpm): 850
Engine	Max power for electrical generation (kWe): 5.9 at 850 rpm
Engine	Max thermal output (kWth): 10.4
Engine	Injector (Bosch): 1 hole
Engine	Injector: 6 holes
Engine	Max power for electrical generation (kWe): 250 at 750 rpm
Engine	Max power (kW): 41.94 kWe/cyl at 750 rpm (56.25 bhp/cyl at 750 rpm)
Engine	Max power for electrical generation (kWe): 250 at 750 rpm
Engine	Injector: 6 holes
Engine	Opening pressure: 200 bar
Engine	Rated Power: 5.4 kW at 3000 rpm
Engine	Rated Torque: 19.6 Nm at 2200 rpm
Engine	Air cooled
Engine	PL-diesel oil emulsions (25/75, 50/50, 75/25 w/w%)
Engine	Fuel cooling after spill return
Engine	Same as Table 3a
Engine	Modified injector nozzle (stainless steel V4A/671-1.4435)

Table 3b. continued
Selected experimental research work on blended/emulsified PL in diesel engines (single or dual-fuel injection)

	[34, 35]		[36, 37]	
	Strictly stock engine, no modifications to the engine and to the fuel supply/injection system Fuel injector spill return diverted to external tank	Surface treatment of injector needle Water jacket on injector tip		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	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) Several hours (typical test duration: 1 h)	20-30 min diesel warm up phase 53-116 min (depending on test nr)	Same as Table 3a 1-3 h (depending on test nr)	Diesel oil Max continuous: 5 h
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	Very fast enlargement of injection channel diameter in the standard nozzle	Similar results to Univ. Florence-Pasquali Reported damages to injector nozzle, tip, needle and fuel pump	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)
Other	Spray visualisation	Emission measurements		External Injection test (EIT)

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 [34 and 35]. 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 [36 and 37] 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 was achieved in a slow speed diesel engine (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 [65], and a detailed investigation on the main characteristics of PL/diesel emulsions carried out, but no engine tests were reported. Recently PYTEC [71] 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 Oy. Twelve hours of efficient operation (on an average of 300 kW power, i.e. 3,600 kWh electricity generation) have been achieved: a mixture of pyrolysis oil (96 vol%) 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) to reduce viscosity.
- Liquid re-cycling has to be limited to prevent fuel quality deterioration (increasing viscosity due to lignin polymerisation, increases lacquering and reduces lubricity).
- Water content smooths the temperature gradient during combustion and is beneficial for NOx 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. [72] in a J69-T-29 gas turbine combustor rig at Teledyne CAE (USA) using slow pyrolysis liquids. Moses [73] and Moses and Bernstein [74] 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 minimised and satisfactory performances and durability guaranteed. Also Boucher et al. [75 and 76], 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 atomisation 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 4) in an extensive experimental program [40, 41, 42 and 43]. 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. The turbine however has a relatively low efficiency of 27.3%.

In preliminary atomisation 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 [40, 41, 42, 43] 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 atomisation (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 [47]: all hot section vanes and blades can now be replaced on site without gas turbine removal. A new on-line hot section cleaning system 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 [46]. 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 [44, 47] and Ensyn [47] pyrolysis oils as well as with other alternative fuels, like ethanol, bio-diesel, and bituminous crude

Table 4. Selected experimental activities on biomass PO use in GTs (whole plant, GT combustion chamber, injection)

	[39,40]	[44,45]	[78]	[76]	[79]
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 assess emissions	To demonstrate power generation from PO in GT To optimize combustion To compare emissions	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 To verify the Rosin-Rammler model
Turbine	Orenda Aerospace GT2500 Max power 2500 kW	Orenda Aerospace GT2500 Max power 2500 kW	Deutz T 216 micro GT Single-shaft Single staged radial compressor and turbine design Dual mode operation TIT 850C Max power 75 kW	Tested GT combustor only, scaled for lab investigation	n.a. Spray investigation only
Load	Idle-part load-full load	Full load	Part load	Part load	n.a.
Tested PO	RTP - wood waste	Dynamotive	BTG-poplar In-line filtered >20µm	Union Fenosa Ensyn RTP 80 (mix PO-EtOH) 115 (PO)	Vacuum pyrolysis-mix of softwood bark
PO preheating (°C)	75	90	Diesel oil	No	80
Pilot flame	up to 100% PO	up to 100% PO	Diesel oil	JP4 (GT CC heating)+spark plug (PO ignition)	n.a.
Start-up fuel			Diesel oil		n.a.
Shut-down fuel	18-19	15-17	14.1	15.3	n.a.
PO LHV (MJ/kg)	1.2-2.0 at 20°C	1.2-1.3 at 15°C	1175 at 15°C	1.26 at 20°C	n.a.
PO density (kg/m3)					1188 at 20°C

Table 4. Continued
Selected experimental activities on biomass PO use in GTs (whole plant, GT combustion chamber, injection)

	[39,40]	[44,45]	[78]	[76]	[79]
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
Atomisation testing (Y/N)	Yes (water-diesel-PO)	No	No	Yes	Yes (water-heating oil-PO)
Spray correlation	No	No	No	Yes-SMID not verified	Yes
Development of prototype nozzle	Yes	Yes	No	No	No
Hot corrosion tests	Yes	No	No	No	No
Combustion tests	Yes	Yes	No	No	No
Po filtration	n.a.	n.a.	Yes	Yes	No
Emission measurements	Flame tunnel test only	Yes. At full load	<20 µm particles At part load	Inline, 60 µm mesh Yes	10 µm mesh 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.

oil [47]. 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 [46]. At full continuous output, the plant is design rated to generate 2,500 kW of electric power and about 5,400 kg/h process steam at over 80% cogeneration efficiency. To date the turbine has been in operation, but few details on operational experiences are reported.

The fuel treatment module [47] 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 [45]. 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 utilised by PLC-based control system [47].

The turbine performed very well with all fuels [44, 47], at different load conditions and during fuel switching. The turbine stabilised 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 5 summarises the measured continuous emission monitor (CEM) emission data at the maximum turbine load of 2.5 MWe. All emissions

data is reported as measured and normalised 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 [47].

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 4) at the Institute for Energy and Environmental Technology of the Rostock University [78]. 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

Table 5. Normalised emissions of various fuel types at maximum load 2.5 MWe [44 and 47]

Fuel	GT inlet		Generator				
	air/exhaust gas temp (°C)	Fuel flow (l/h)	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 Ontario emissions limits	5.6/467	1055	2510	4.4	14.8	326	421
				60	189	86	

n-readings normalised to 15% oxygen. Turbomachine rotational speed was about 14 000 rpm.

atomisation 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 characterisation were carried out in Spain and Canada [45] and [79].

The University of Madrid [46] 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 atomiser 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 [80, 81, 82, and 83], 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 [79]. 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, 7.36×10^{-8} m²), 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 atomised using commercially available atomisers 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 atomisation, 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 atomisation 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. 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 [84]. 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 atomisers (agglomerates) and the fuel supply (solids in PL) were reported. Efficiencies were low, possibly due to the use of un-preheated combustion air.

4. Cost of electricity generation from pyrolysis liquids in dual fuel diesel engines

The inherent requirement for the use of pyrolysis liquids in power generation is that it can be done economically and compete in the long term with the costs of conventionally derived electricity. Work done by Peacocke et al. has shown that the costs of production of electricity in dual fuel diesel engines are at present too high for the UK market [85], with a zero cost feedstock required or preferably a cost for disposing of the biomass. Plants below 10 MWe would not appear to be commercially attractive in the short term. Utilisation of co-products for other non-energy uses is one possibility and use of a proportion of the liquids for resins, slow release nitrogenous fertiliser, food flavourings and bio-char [soil amendment] are potential longer term options.

5. R&D needs and conclusions

The use of PL for power generation requires standardisation 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):

- Uniform-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 ageing test "24h-80°C" (which correlates to the changes occurring during 1 year at room temperature). Possible alcohol addition.

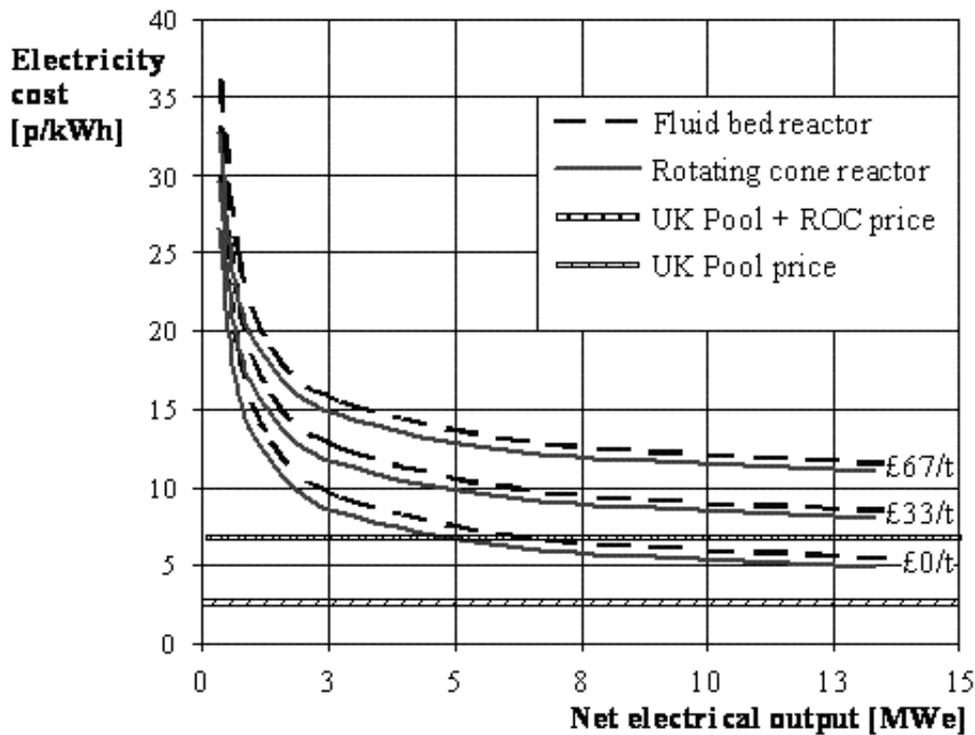


Figure 5.

Electricity Production Costs vs Net Electrical Output [MWe] and feedstock cost [€/dry t] for a fluid bed process [Wellman] and the rotating cone process of BTG, the Netherlands [85]. Variation with feedstock cost [£67/t, £33/t and £0/t]. August 2004 costs

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 decentralised 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 technically 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 more thermally stable to tolerate liquid recycling in injection systems. 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 or build-up 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.

The supply cost of PO is the critical issue to achieve market penetration: estimates by Wagenaar et al. [86], 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. This venture has stopped due to changes in the support for renewable fuels in the Netherlands. The plant in

Malaysia has therefore been mothballed. The status of development of these alternatives is summarised in Table 6.

There is a need to reduce the cost of production, possibly by improvements in power generation efficiency, by using modern high efficiency dual fuel diesel engines and more efficient turbines, however, this may be viewed as a longer term objective. The inclusion of biomass pyrolysis into an overall "bio-refinery" approach may allow for part production of liquids and char for non-energy uses, improving the economic viability of the technology.

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 Centre 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; RTP™, Enslyn Rapid Thermal Process, Canada; SMD, sauter mean diameter; TIT, turbine inlet temperature; VTT, Technical Research Centre of Finland.

6. References

References available from IDGTE Web Site: www.idgte.org

Table 6. Status of PL-based power generation technologies

	Gas Turbine	Diesel Engine	Stirling
Development stage	2,500 kW modified system ready for commercial demonstration No other modified GT plants available	Several engines tested: reliable system not yet developed Various activities ongoing	Short-term testing carried out in a very small unit
Major modifications, critical issues	Nozzles, materials, in-line cleaning system, feeding line Long-term commercial demonstration	Injector and fuel pump material emissions Development of: effective/reliable pumping and injections systems; good combustion to avoid deposits on the hot parts (cylinder, piston, injector); materials	Pump and injector Reliable small scale Stirling engine to be developed and long-term demonstrated with standard fuels before carrying out further tests on PO
R&D needs	Modification of other GT turbomachines Demonstration of combined cycles		
Further developments	Application of PO to MGT	Use of emulsions and blends for ignition, fuel handling and injection improvement	As above



Q John Blowes

Are the acids mentioned mostly 'organic'?

A The acids are all organic acids, predominantly acetic and formic acid which are usually present up to about 5wt% from woods. There are also some phenolic acids, but in relatively low quantities.

Q Do operating costs include the cost of overhaul and if so what is the period between cylinder head overhauls?

A The costs quoted include all overhaul and servicing costs. It is expected that cylinder head overhauls may be required possibly twice as often, however this is only speculative without long term operational experience.

Q With poor commercial viability for use of pyrolysis oils in reciprocating engines and gas turbines; has funding been mostly Government grant aided through the R&D stages?

A Yes, the work in the UK has been supported by Government. The first plant was built by Wellman Process Engineering Ltd. in 2002 with a capacity of 250 kg/h and was supported by the DTI. A second pilot plant with a capacity of 250-300 kg/h is presently being constructed by Biomass Engineering Ltd., again supported by the DTI/BERR. Outside of the UK, the BTG plant in Malaysia of 2 t/h is a commercial venture and the plants built by Dynamotive in Canada and Ensyn in the USA are commercial units.

Q John Kitchenman:

The author referred to severe mechanical wear occurring to a diesel engine burning pyrolysis liquid reformed from wood chip; was this just to the fuel injection equipment (fuel pumps, injectors and nozzles) or were other components affected? Was the wear corrosion damage, or scuff damage due to poor lubrication and can it be counteracted by changes in component materials? Would the same wear occur if the pyrolysis liquid had been reformed from household waste?

A Most wear has been detected in the fuel injection equipment as noted. Wear has been a mixture of acid attack on mild steel components and needle/nozzle erosion from the presence of fine particles in the liquids. Erosion can be

avoided by careful materials selection or ceramic coatings. The acid attack would be the same for liquids derived from household wastes. The acidity cannot be "neutralised.", as the low pH inhibits polymerisation of the liquid.

Q Please advise if pyrolysis liquid can be blended with other renewable liquid fuels and whether a blend/mixture is available that reduces the wear problems reported? If this blend is made into an emulsion in an homogeniser could the wear be further reduced?

A Pyrolysis liquids can be blended with biodiesel or conventional diesel and there has been a lot of work done on the latter. Some blends have been noted to cause wear as mild steel engine components have been used. Due to the organic acids, a change of fuel injection materials to stainless steel or coated parts is recommended.

Q Does the author have any information on what success has been achieved by Jenbacher with their development of running on pyrolysis gas in Germany and Belgium?

A Jenbacher have extensive experience in the burning of low CV gases, down to 1.2 MJ/Nm³, but I'm not aware of the combustion of pyrolysis gases per se in engines. They do have significant experience in using their 3 and 6 series engines burning producer gas, for example there is one JMS 620 GS-S.L series engine burning producer gas [3 kWh/m³] from the Güssing biomass gasification plant in Austria, generating 2 MWe. There are several other small scale projects using 1 or 3 series engines in Germany and Austria.

Vote of Thanks by John Blowes

The Engineer is noted for his innovation and ability to make the system work, given the right incentive. This has clearly taxed innovation to the limit and we are full of admiration for the Author's, Ormrod and other efforts to make diesel engines and gas turbines operate on a fuel that is slow to burn, very acidic, has no lubricity and quickly changes state.

May I thank you on behalf of the Institution for compiling and presenting such an interesting paper that records progress to date and with clear and concise technical and commercial viability information.