HOGERE ZEEVAARTSCHOOL ANTWERPEN

FACULTEIT SCHEEPSWERKTUIGKUNDE

An approach to fast pyrolysis-oils as diesel fuel additive

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Scriptie voorgedragen tot het behalen
Bachelor in de Scheepswerktuigkunde

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Trying a new road may not be the easiest way to your destination,

but you might discover a thing or two”.

- Larsen Priem

Acknowledgements

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I would like to take this opportunity to express my gratitude to my family.
My parents and sister who supported me through my education, from the early morning to the late nights; I owe you both more than I can ever repay. To my both grandfathers; thank you for teaching me valuable skills and lighting the spark of curiosity in me. To my both grandmothers thank you for letting me discover and experiment in your houses and gardens.

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Abbreviations

AC: Alternating current (Electricity)

AMA: Antwerp Maritime Academy (Institution)

bar(g): bar gauge (Pressure)

bp: boiling point (Fuel characteristic)

CCAI: Calculated Carbon Aromatic Index (Fuel parameter)

DC: Direct current (Electricity)

DMA: Diesel for Marine Application (Maritime Fuel)

ECN: Energieonderzoek Centrum Nederland (Institution)

EGR: Exhaust Gas Recirculation (Emission control system)

cSt: Centi stokes (kinematic viscosity)

ENSYN: Ensyn Fuels Inc. (Company)

fp: flash point (Fuel characteristic)

FPO: Fast Pyrolysis Oil (Bio-fuel)

Hc: heat transfer coefficient (Heating efficiency)

HFO 380: Heavy Fuel oil with a density of 380 cSt at 50°c (Maritime Fuel)

HHV: Higher Heating value (Fuel efficiency characteristic)

HZS: Hogere Zeevaart School (Institution)

IFO 180: Intermediate Fuel Oil with a density of 180 cSt at 50°c (Maritime Fuel)

IMO: International Maritime Organisation (United Nations Institution)

kWe: kilo Watts electrical power (Unit for power)

LHV: Lower heating value (Fuel efficiency characteristic)

MEPC: Marine Environment Protection Committee (IMO organ)

MGO: Maritime Gas Oil (Maritime Fuel)

MWe: Mega Watts electrical power (Energy)

NO_x: Nitrogen Oxides (Emission)

NREL: National Renewable Energy Laboratory (Institution)

PAH: poly aromatic hydrocarbons (Emission)

PV: Present Value (Automation parameter)

RMG 380: Marine Residual Fuel with a density of 380 cSt at 50°c (Maritime Fuel)

SECA: Sulphur Emission Control Area (IMO legislation)

SO_x: Sulphur Oxides (Emission)

SP: Set Point (Automation parameter)

SV: Set Value (Automation parameter)

$t\ ha^{-1}\ y^{-1}$: Ton per hectare per year (crop yield)

VOC: Volatile Organic compounds (emissions)

VVT: Technical research center of Finland (Institution)

WHSV: weight hour space velocity (mass flow rate vs catalyst mass in reactor)

wt. %: weight percent (amount of mass)

ZSM-5: Zeolite Socony Mobil–5 (catalyst)

Nederlandstalig abstract

Deze professionele bachelorscriptie evalueert het gebruik van snelle pyrolyse-olie (FPO: *fast pyrolysis oil)* als hernieuwbare energiebron voor industriële en maritieme toepassingen, inzonderheid als brandstof voor maritieme dieselmotoren.

In de eerste sectie bestuderen we bamboe als biomassagrondstof omwille van zijn wijdverbreide toepassing, lage productiekost, calorische waarde en hoge opbrengst. Om het werkingsprincipe van gefluïdiseerde bedreactoren beter te kaderen, zetten we de ontwikkeling van het pyrolyseproces uiteen aan de hand van het houtskoolproductieproces.

We onderzochten verschillende wetenschappelijke publicaties om tot een overzicht te komen van pertinente FPO-kenmerken die we vervolgens gedestilleerd hebben tot een algemeen overzicht. Hierna hebben we deze cijfers naast die van moderne maritieme bunkerbrandstoffen gelegd en kritisch onder loep genomen. Verder bespreken en beoordelen we enkele praktische tests met FPO in snel- tot middelsnellopende dieselmotoren, afkomstig uit de vakliteratuur.

We concluderen dat FPO een geschikte bunkerbrandstof kan zijn voor maritieme toepassing wanneer men gebruik maakt van bamboe als grondstof.

In de tweede sectie bespreken we de reparaties, modificaties en verbeteringen uitgevoerd op de pyrolysereactor van de Hogere Zeevaartschool Antwerpen in het kader van deze scriptie. We hebben op deze reactor praktijkonderzoek met geconditioneerde biomassa uitgevoerd. Deze ervaring is omgezet in een praktische gebruikershandleiding voor de testreactor die u terugvindt in het addendum. De handleiding bevat een volledige beschrijving van de reactor, zijn procedures en veiligheidsvoorschriften.

Uit het praktisch onderzoek met de testreactor blijkt dat zijn huidige configuratie het wel in staat stelt om FPO te produceren voor onderzoeksdoeleinden maar zijn capaciteit ontoereikend is voor realistische tests in dieselmotoren.

Deze scriptie is met toelating van de HZS-administratie volledig in het Engels geschreven om de inhoud open te stellen naar een breder internationaal publiek en een volledig beeld van de competenties als scheepswerktuigkundige weer te geven. Een kopie van de toelating is bijgevoegd in het addendum.

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Abstract

This professional bachelor thesis evaluates the use of fast pyrolysis oil (FPO) as a renewable energy source for industrial and maritime applications, in particular as fuel for maritime diesel engines.

In the first section, we study bamboo as biomass feedstock for FPO because of its wide application, low production cost, heating value and high production yields. For a better understanding of fluidised bed reactors, we explain the evolution of the pyrolysis technique starting from the originating charcoal production process. We researched several scientific publications to generate an overview of the pertinent FPO characteristics that we subsequently distilled into a general overview. Hereafter we compared the data with those of modern maritime bunker fuels. Further we discussed and assessed practical tests of FPO application in high to medium speed diesel engines, derived from specialized literature.

We concluded that FPO can be a suitable bunker fuel for maritime application when using bamboo as biomass feedstock.

In the second section of this thesis we discuss repairs, modifications and improvements executed on the Antwerp Maritime Academy pyrolysis reactor. For this thesis, several practical tests with conditioned biomass (pine and bamboo) were executed on the AMA-pyrolysis reactor. This experience is translated in a practical user manual which you can find in the addendum section. The manual contains a complete reactor description, procedures and safety instructions.

It is apparent from the practical research that the current configuration of the AMA-reactor is able to produce FPO for research purposes, however its capacity is insufficient for supplying realistic tests with diesel engines

This bachelor thesis is written completely in English with permission of the AMA administration. This to enhance accessibility for a wider international public and to provide a complete picture of the skill set of a marine engineer.

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1 Introduction

1.1 Bamboo

Garden pest and biomass goldmine

The overall population in western countries will see bamboos (Figure 1) as an invasive species (USDA, 2017). Winter green and creeping faster than ivy, rising to the sky or spreading in to an impenetrable bush, once let loose it can be the end of the long-lasting peace between neighbours. On the other hand, we all like to grow the most exquisite exotic plants in our garden to impress those same neighbours.

Figure 1. Figure 1 Phyllostachys aurea

(https://gardenesia.com/products/exotic-plants/golden-bamboo/)

But bamboo is not a single plant species. Today the crop counts a total of 1400 known species of bamboo worldwide, with many still being discovered (Clark, 9th World Bamboo Congress Belgium, 2012). Bamboo: *Bambusoideae* (*Poaceae*: grasses) comprise three distinct and well-supported lineages: tropical woody bamboos (*Bambuseae*), temperate woody bamboos (*Arundinarieae*) and herbaceous bamboos (*Olyreae*) (Wysocki, 2015). These giant grasses, are not trees or bushes like many people presume. Thousands of years ago, bamboo was spread across the whole continent from Japan to Europe but the last ice ages meant the end of its existence in Europe. (Kumar, 1999) Today it grows in South-Asia, East Africa, South, North America and is cultivated in Europe. Looking like it prefers a hot to moderate climate. There are species who prefer the humid heat of the jungle, the freezing and rocky terrain of the Himalaya or even the hot dry sands of the desert. Its adaptation to many climate forms ensures that you will be able find a bamboo specie for every patch of soil. Its wide spreading around the globe, makes that bamboo is adapted to these different climates, which makes it hard to give bamboo general specifications. The winter resistant species, mostly originating from mountain area’s in the east, easily adapt to the weather in Europe (Clark, 2005). The African continent’s Sahara, can be a home for the bamboo species that have adapted to living in water scares deserts.

Morphologically, the bamboo family can be divided in to two big branches: sympodial and monopodial bamboos. To simplify: the bush-forming (clumping) and the solitary bamboo. Their growth and behaviour originates from the difference in their rhizome (subterranean horizontal shoot) structure. This structure, together with the leaves are the first two easy ways to classify bamboo.

The sympodial branch of the bamboo family has two siblings:

- The sympodial-tufted bamboo part of the bamboo family has bush-forming characteristics. The plants form big patches of almost impenetrable bamboo bushes. (Figure 2)

Figure 2. Sympodial-tufted bamboo

(https://www.guaduabamboo.com/identification/types-of-bamboo-rhizomes)

Example: *Fargesia frigida* T.P.Yi

- Sympodial-scattered bamboo is a second variety of sympodial bamboo. This plant forms false rhizomes up to a meter long. (Figure 3)

Figure 3. Sympodial-scattered bamboo

(https://www.guaduabamboo.com/identification/types-of-bamboo-rhizomes)

The growth structure of this bamboo is scattered widening patches connected by false rhizomes that have no auxiliary buds on the rhizome itself.

Example: *Guadua angustifolia* (South-America)

The monopodial branch of the compromises bamboos with culms that rise to the sky, featuring more solitary shoots that grow up to 10 meters high and up to decimetres thick. This part of the bamboo family has more in common with trees than bushes. The wood content is much larger than that of the sympodial bamboo, which develops more leaves and less lignified branches. (Figure 4)

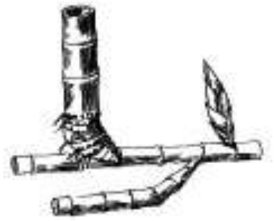


Figure 4. Monopodial bamboo

(https://www.guaduabamboo.com/identification/types-of-bamboo-rhizomes)

This horizontal network of roots consists out of rhizome branches connected by nodes. From these nodes, small roots and leaves emerge, each node has one bud or more. These buds sprout new rhizomes or grow to the surface in the form of shoots that can develop into new stems. The rhizome structure can spread for miles. A small bamboo forest can be formed from one widespread rhizome network.
Example: *Phyllostachys aurea* (Golden bamboo)

The mixopodial branch features a combination of both sympodial and monopodial characteristics. This odd brother of the family blurs the strict line between the monopodial and sympodial characteristics. (Figure 5)

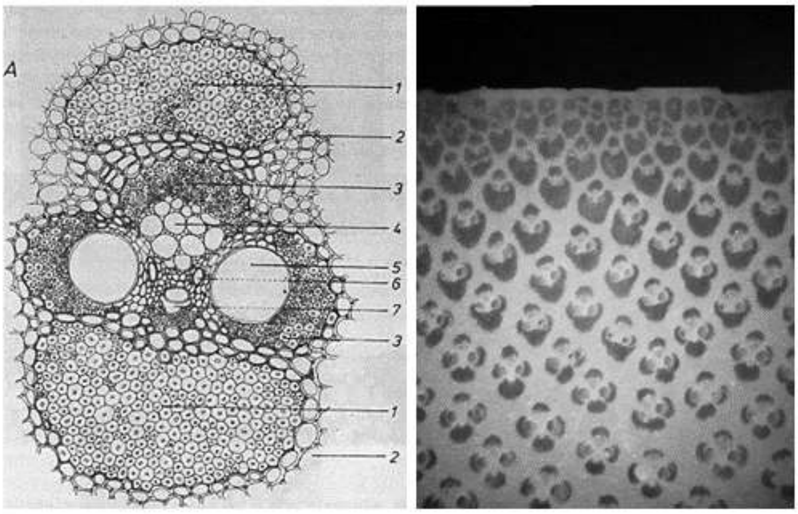
Example: *Semiarundinaria fastuosa*

Figure 5. Mixopodial bamboo

(https://www.guaduabamboo.com/identification/types-of-bamboo-rhizomes)

The third odd brother grows a scattered rhizome network like monopodial bamboo with sympodial concentrations of bamboo patches. This structure must not be confused with the sympodial-scattered root structure which does not feature nodes in the 'false' rhizome connections between the clumps (Schröder, 2014).

1.1.1 The beauty of bamboo cell structure



Details of vascular bundle:
1 Fibre strand
2 Parenchyma
3 Sclerenchyma sheaths
4 Phloem (sieve tubes with companion cells)
5 Metaxylem (vessel)
6 Smaller metaxylem element
7 Intra-cellular pathways (protoxylem)

Figure 6. An overview of the cell structure of Phyllostachys edulis.

by (Schröder, 2011)

The composition of *Phyllostachys edulis* and other bamboos is a mix of hemicellulose, cellulose and lignin which make up more than 90% of the total dry mass. (Li, 2015) The sum of hemicellulose and cellulose is about 65%. The high lignin content (20 – 40 wt. %) makes bamboo an interesting feedstock for aromatic chemicals (de Wild, 2015). Hemicellulose is part of the cell wall and composed of carbohydrates of which most are sugars. (Scheller, 2010) In bamboo, hemicellulose is mostly composed of pentosane with little hexoan, 90% Of the hemicellulose in bamboo timber(culms) is made up of xylan. Bamboo xylan is D-glucuranate arabinoxylan, which comprises 4-oxygen-methyl-D-glucuranate, L-arabinose and D-xylose. The molecular ratio is respectively 1.0:1.0-1.3:24-25.

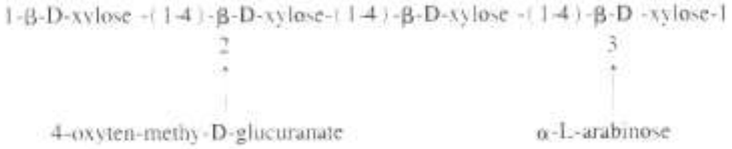


Figure 7. Chemical composition of bamboo xylan

by (Fy, 2007)

The composition of arabinoxylan of bamboo is different from that of conifers and broad-leaved trees. The polymerized molecules of bamboo xylan are more present than those in wood from trees. The content of pentose in bamboo timber is 19-23%, which is close to that of broadleaves and much higher than that of conifers (10-15%). This indicates that bamboo timber can not only be used to make pulp or for fuel by pyrolysis and hydrolyse processes, but can be used as synthetical uronic acid (sugar acids) (Fy, 2007).

Bamboo lignin is comparable to lignin from herbaceous plants. It is composed out of three phenyl propane units, i.e. paradinum, guaiacyl(monomer) and mauve lignin in a respective ratio of 16:68:22. This means that, quantitively, the bamboo lignin can be compared to broad-leaved. The specific features of bamboo lignin, lie in the existence of dehydrogenated polymerides and 5 to 10% acrylic esters. The lignin content of one-year old bamboo is in the range of 20-25%, approaching that in broad leaved trees and some other grasses (such as wheat straw 22%) and is little lower than that of conifers (Fy, 2007)

1.1.2 Reaching for the sky

Bamboo has the highest grow rate of all plants. In no time, it turns from a mere weed into a cm thick stem reaching higher than a grown man. Figure 8 shows the development of a single *Phyllostachys edulis* shoot into a culm in less than a month.

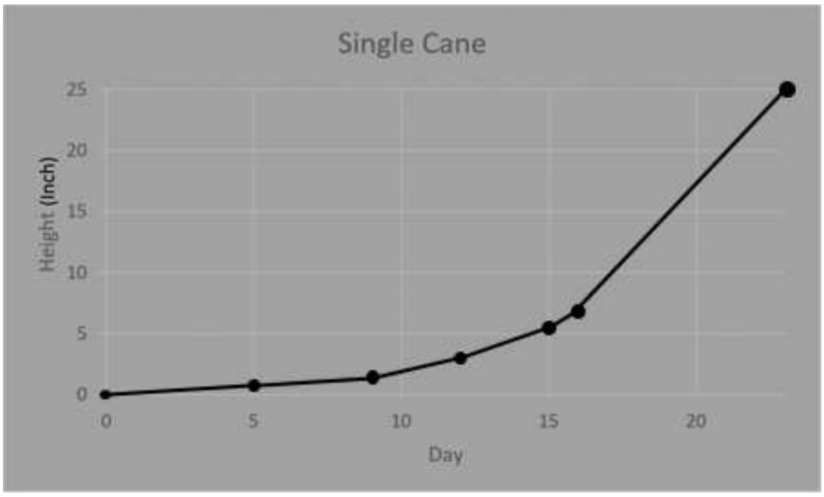


Figure 8. The growth rate of a single Moso bamboo shoot.

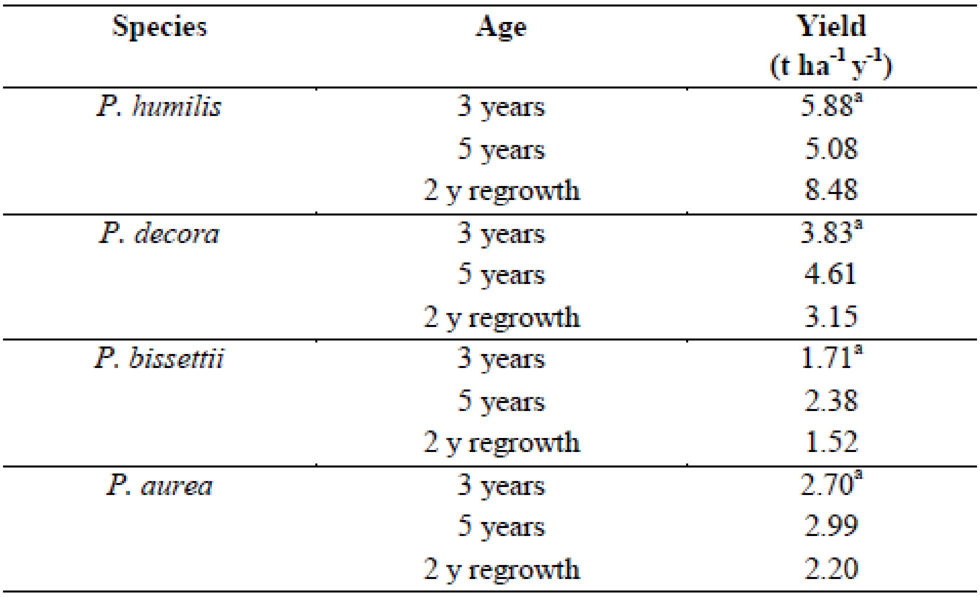
(https://lewisbamboo.com/growth-chart-of-bamboo/)

This characteristic gives it a huge advantage compared to other grasses and trees. The renewal rate of a bamboo forest is many times faster than that of a forest for the same amount of wood. A big positive point is that bamboo is “winter green” and grows throughout the whole year. Growth can be impacted by frost and drought (Fy, 2007).

Table 1 describes the biomass yields of four *Phyllostachys* species grown on a test plantation in Ireland (Potters, 2009), (Van Goethem, 2013).

Table 1. Bamboo yields for different Phyllostachys species.

Grown on a crop field in Ballyboughal, co. Dublin, Ireland. (Van Goethem, 2013)



Species	Age	Yield (t ha^{-1} y^{-1})
P. humilis	3 years	5.88[a]
	5 years	5.08
	2 y regrowth	8.48
P. decora	3 years	3.83[a]
	5 years	4.61
	2 y regrowth	3.15
P. bissettii	3 years	1.71[a]
	5 years	2.38
	2 y regrowth	1.52
P. aurea	3 years	2.70[a]
	5 years	2.99
	2 y regrowth	2.20

1.1.2.1 Soil requirements

Bamboo grows optimally in a rich and drained sandy loam soil. A soil pH between 5 and 6.5 is ideal. It grows well on poor and contaminated soils and a more acid soil has less impact on bamboo than on other crops. Some examples of extreme survivability of bamboo: the *Phyllostachys atrovaginata* which survives soil acidity up to pH3.3. Even on slightly salty soils, where most plants wither and crumple, *Phyllostachys vivax* grows without any problem (Schutte, 2010).

1.1.2.2 Water requirements

For bamboos growing in Europe, the genera *Phyllostachys* and *Fargesia* can survive on 750 to 1000mm rain fall per year. Because of the high stress resistance and adaptivity of these bamboo species, they can survive in Europe (Schutte, 2010). Gardeners are growing bamboo in the deserts of the American southwest, as well as the high deserts of Idaho, Oregon and California. Extreme bamboo species that are grown in desert climates include *Otatea aztecorum* "Mexican Weeping Bamboo," native to the Sonoran Desert of Mexico, and *Phyllostachys aurea* "Golden Bamboo," (de Jauregui, 2017).

1.1.3 From tool shed to stir fried noodles soup

Traditionally bamboo is used in Asia for many purposes: construction materials, paper, weaving material, food(shoots), charcoal, composite materials, firewood, tools and more. The sympodial bamboo family is used for applications that requires less structural strength and where the form of the bamboo is less important, for example: paper and compressed charcoal. The monopodial bamboo can be used for more structural applications, like building material and furniture (Fy, 2007).

Bamboo is a very strong but light material; the fibre is so strong; you can compare it to steel. The longitudinal bamboo fibre (1.5-3.2mm) is longer than most wood fibres except for pine (3-4mm). (Schutte, 2010) Because of its hollow structure the culms are very light compared to other renewable construction materials. Bamboo being a natural material, the weight is much less than steel. However, bamboo has more than twice the unit strength-weight ratio than that of steel (Mahzuz, 2013).

Table 2. Ratio of strength and unit weight compared for bamboo and steel.

(Mahzuz, 2013)

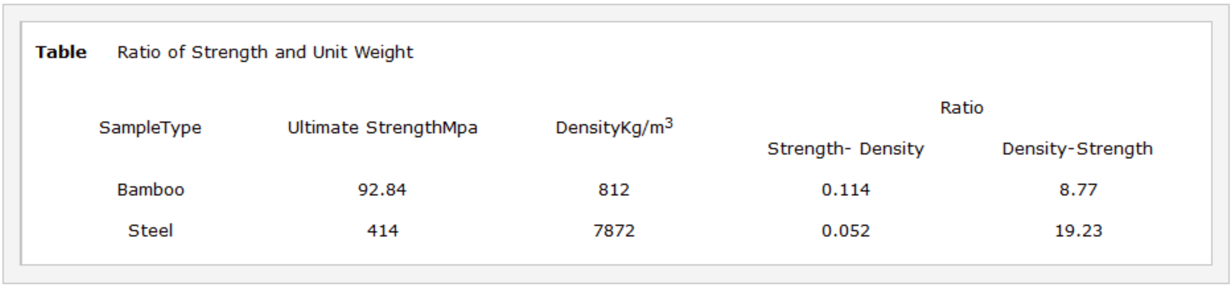


Table Ratio of Strength and Unit Weight

SampleType	Ultimate StrengthMpa	DensityKg/m^3	Ratio	
			Strength- Density	Density-Strength
Bamboo	92.84	812	0.114	8.77
Steel	414	7872	0.052	19.23

The strong fibre structure of bamboo requires that operational processing machinery needs to be equipped or modified to handle this kind of though material. All these characteristics make bamboo a material that can optimise constructions, it is also a very potent resource that can replace many base products in the traditional industry (Potters, 2012).

1.1.3.1 Exploitation

Growing bamboo is not very difficult, but growing it as a profitable energy crop requires more than a patch of soil under the sun. Nowadays bamboo seedlings are produced in a cost effective in way by *in vitro* culture. The older and more labour-intensive alternative is dividing the roots into more plants (Schutte, 2010).

Yields of crop are dependent upon the weather, rainfall and soil quality. We can fertilise the soil and irrigate the fields, but the climate can be quite unpredictable. Bamboo will grow better in stable climates with moderate amounts of rainfall and soft winters. The Mediterranean climate is a proven success story (Messerli, 1992).

1.2 Conditioning of biomass

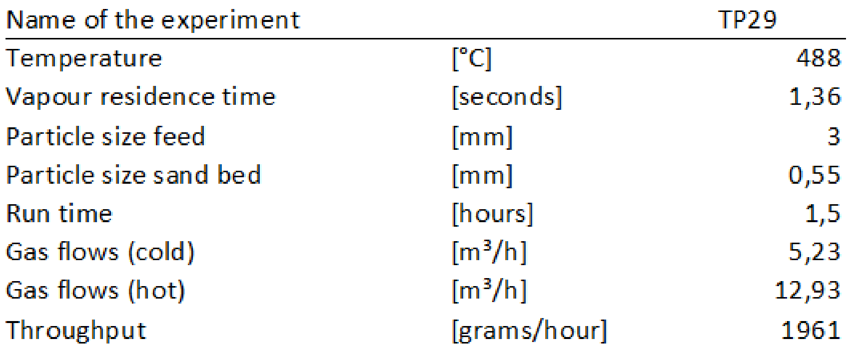
Biomass needs to be conditioned to obtain certain characteristics before it can be used in the fast pyrolysis process.

1.2.1 Particle size

One major parameter for the fast pyrolysis reaction is the particle size of the source material. This is applicable for biomass but also for other resources. The particle size is in direct relation with the residence time of the material, which in turn affects the quality and quantity of the pyrolysis oil. To break down the material in the reactor a certain amount of energy is needed: the bigger the particle, the more energy is required to break it down. And thus, the total residence time of the gases and vapours is affected if the particle needs to reside longer in the reactor. The molecule structure of the vapour products is degraded further to lighter components, which no longer contribute to oil production and stay in gaseous form under atmospheric conditions.

Table 3. Pyrolysis conditions used for bamboo

(Meier, 1999)



Name of the experiment		TP29
Temperature	[°C]	488
Vapour residence time	[seconds]	1,36
Particle size feed	[mm]	3
Particle size sand bed	[mm]	0,55
Run time	[hours]	1,5
Gas flows (cold)	[m^3/h]	5,23
Gas flows (hot)	[m^3/h]	12,93
Throughput	[grams/hour]	1961

Particles must be very small to fulfil the requirements of rapid heating and to achieve high liquid yields. Feed specifications range from less than 200 mm for the rotating cone reactor to less than 2 mm for fluid beds and less than 6 mm for transported or circulating fluid beds. Ablative reactors can utilise whole tree chips as the mechanism of heat transfer is different. Size reduction becomes increasingly expensive as size reduces and reactors using larger particles have an advantage in this respect (Bridgwater, 2000).

A high bio-oil production requires a very low vapor residence time (typically 1 second) to minimize secondary reactions; however, reasonable yields can be obtained at residence times of up to 5 seconds if the vapor temperature is kept below 675 K. In contrast to slow pyrolysis, fast pyrolysis is an advanced process, which needs to be carefully controlled to produce high yields of bio-oil. A typical reaction temperature of around 775 K is employed (Babu, 2003).

Many different sources: (El Bassam (1998) Bridgwater (1999), Demirbas (2010), Garcia-Perez (2010), de Wild (2015)), recommend different particle sizes, mostly between 1 to 5mm and residences time up to several seconds. This is highly dependent on the way of heat transfer, reactor construction and the demands of the raw material used.

The small particle size is also an advantage, biomass of almost any size can be used, from sawdust of lumber mills to residues of production processes. The only way to accomplish particle size reduction to the required size, is mechanical shredding and grounding of the material, the larger the size of the source material to begin with, the more energy it will require to be reduced to the predetermined size.

There is much industrial and conventional shredding machinery available, few meet the required mm precision demanded. A combination between panning and re-shredding of the oversized material is a solution. However, this not a very economical one. Investment in the development of high capacity multistage precision shredders is necessary to meet the required conditioning demands for the pyrolysis oil production.

Water content of the pyrolysis oil is influenced by the water content of the material introduced into the reactor. Because the oil is mainly composed out of water miscible liquids, it is easily miscible in water and vice versa. The main product, bio-oil, is a miscible mixture of polar organics (about 75±80 wt. %) and water (about 20±25 wt. %). (Bridgwater, 1999) The water in the oil is difficult and costly to remove. The solution is decreasing the water content of the feed material by drying it. There are various ways to accomplish this, but economically, the most water is the most easily removed by exposing the feedstock to hot air (+200°C) for several hours. Forms of waste heat recovery should be considered to accomplish this.

1.2.2 Storage and transport

Biomass is prone to decay when exposed to humid conditions. Even when stored in a dry and cool place, fungi and moulds may develop because of the spores and traces that remain on the biomass. The solution is to reduce the time between harvesting and drying.

It can be economically beneficial, especially in dry climates, to dry the biomass naturally for a certain period. In more humid climates this should be avoided.

The process of forced drying of the shredded material, after the harvest will reduce the water content but also kill parasites, fungi and moulds, that are present in the biomass. This will not only greatly prolong the maximum storage time, but makes the biomass more efficient to be stored and transported in sacks, bags, silos, containers or as bulk cargo. It is thus a big advantage to keep the distance between the production and the processing industry as short as possible. Once conditioned the biomass can be shipped and transported without any problem. The distance between the processing industry and the consuming party or industry can be half a globe apart, only the cost and required energy of the transportation must be considered.

1.2.3 Bamboo processing compared to pine grounding

A big difference between biomass source material from plants and recycled plastic is the fibre structure of the biomass. While the plastics can be easily grounded in spherical and cube shaped material, biomass tends to be more reluctant to shredding because of these strong fibres. A big parameter is the length and strength of the fibres in the biomass. We can easily see the difference between pine wood and bamboo.

Figure 9. Shredding of bamboo (left) and pine (right)

by Larsen Priem

Pine wood is reduced to shorter and thicker particles compared to the bamboo that features longer and more wiry splinters, even though both have been subjected to the same shredding procedures and machinery. The different result lies in the anatomical difference of the fibre and the structure of the vascular tissue (wood & bark).

1.3 Pyrolysis

1.3.1 Bamboo charcoal the grandfather of fast pyrolysis

The charcoal process is centuries old and a very effective way to produce a qualitative energy source with high energy density. Nowadays there is discussion (Tunde, 2013) & (Chidumayo, 2012) about the question whether it is better to use charcoal, which has many benefits, or to use the wood directly, which removes the obsolete energy consumed in the charcoal transformation. By heating up wood or biomass in oxygen poor conditions, the volatile and unstable products in the wood are released and the structure of the wood becomes carbonized. This carbonized wood (charcoal) is a carbon rich fuel containing next to no water. Bamboo charcoal burns hotter and longer, while producing less smoke. This characteristic makes it an excellent fuel source. Other than as fuel source, pure charcoal is used in applications like filtration of fluids and water treatment (Fy, 2007).

Charcoal furnaces are mostly fuelled with inferior wood or scraps, even than extra conversion is considered thermodynamically to be a loss of energy. These furnaces and ovens are also called kilns. They vary from hand operated brick build constructions to massive concrete silos for large scale production (Fy, 2007).

In the case of bamboo, it can be very interesting to convert the material to charcoal. Burning dry bamboo is a tedious job, it burns very quickly and it is very hard to reduce. The amount of bamboo used for heating purposes will be higher than hardwood, even though the caloric value is comparable. Another problem is that bamboo contains a lot of water, which on its turn reduces the heat production. By converting bamboo to charcoal these problems are solved (Meier, 1999).

The bamboo industry produces different products. Except for the young shoots, that are eaten, most of the products originate from the bamboo stems. The leaves and large numbers of smaller branches are left over. The conversion of this left-over biomass to compressed charcoal briquettes is a beautiful example of waste stream management (Fy, 2007).

1.3.1.1 Why grandpa charcoal needs retirement

There is only one problem with bamboo charcoal: because of its solid state, application can only be as a direct thermal energy source. This makes it suitable for heating, but less desirable for conversion to mechanical power, where the application depends on steam generation and a third energy conversion in turbines.

The more efficient way is using combustion engines that run on liquid fuels, they have higher energy conversion rates (50%) and no third energy conversion is required. (Chiaramonti, 2007)

And here we reach a problem. The solid structure and high carbon content of the charcoal is also one of its biggest disadvantages. The combustion of carbon rich matter produces high amounts of particular matter (PM) and other toxic products, which have severe health consequences (Semple, 2010).

If we look back at our base product, biomass (bamboo), we see that we have excluded a fraction of its embedded energy. This fraction is separated from the biomass during the charcoal heating process. The charcoal fabrication process is a form of biomass gasification. The vapours and gases that are released by the wood can’t escape the charcoal furnace and are further decomposed by the heat.

1.3.2 Pyrolyzing future fuel from our dark charcoal past

During the gasification, the cellulose, hemicellulose and the lignin are decomposed (cracked) to lighter fractions. The volatile and unstable elements leave the wood when it is carbonized (pyrolyzed) and are left out of the equation. These compounds are energy rich and valuable.

When the gases and vapours are extracted from the furnace, we can use this energy for other purposes. Burning them directly in a turbine or adapted petrol engine is a possibility.

The other option is trying to capture these gases. We can compress them into cylinders, a more efficient way is to cool them down. A big fraction of these gases are liquids suspended in vapour phase.

By cooling them down beneath their vapour temperature they will turn in to liquids. The further those elements are decomposed the ‘lighter’ they are. These lighter elements, like methane need lots of energy to be liquefied (boiling point methane-163°C).

Many factors influence the production of condensable vapours. The most important are: gas displacement, oxygen content, temperature, conditioning and size of the used biomass.

When the gases and vapours are extracted from the furnace, an equal volume must be replaced. In a classic bamboo charcoal kiln, extra air is sucked in to compensate the under pressure. The gas is pushed out by this natural flow, but not very effectively. The addition of extra oxygen into the charcoal procedure will reduce the production and turn more wood into ash.

As mentioned before, oxygen introduction will have a negative effect on the charcoal and pyrolysis oil yields of the charcoal furnace. The charcoal process aims to have a small to non-existing amount of oxygen in the furnace. Oxygen addition will allow the biomass to burn instead of pyrolyze. These classic furnaces are not air tight and, air is drawn in through cracks and seeps.

The average temperature in a charcoal furnace depends on the stage of charcoal purification (Fy, 2007). By increasing the temperature, the gasification rate will increase as well. On the other hand, the extra energy translates into increased cracking of the elements released by the wood. This increased degradation of the heavier elements to lighter elements will reduce the amount of condensable vapours and transform them into lighter gases.

When producing charcoal, big and large chunks are desired. The bigger the biomass to begin with, the more energy is necessary to completely carbonize it to its core. The balance between good grade charcoal and low energy consumption is hard to strike.

For medium to high grade bamboo charcoal, arm length bamboo stems are placed into the oven. The bamboo is heated in up to three stages (+260°C, +450°C and +1000°C). Three stage bamboo charcoal is the purest and richest form. This full culm charcoal takes more energy, than when we pyrolyze leaves and smaller branches. This biomass needs less energy to be converted, because the particles are smaller and require less energy to be carbonized to the core. The process yields small shards of charcoal, to effectively use this fuel it is compressed into briquettes (Fy, 2007).

By analysing the weak points and adapting the principle of the charcoal production by addition of new elements to the process we come to following conclusion. We need to increase the temperature of the reaction to lift the pyrolysis yields. This will increase the degradation of the valuable vapours we try to capture; this is solved by reducing the residence time in the heat. To accomplish the same level of cracking, with a shorter residence time, the size must be reduced to particles of mere millimetres in dimension. Particle reduction will lower the required amount of energy. To reduce the oxygen content, we modify the brink build furnace to a stainless-steel reactor with an atmosphere controlled environment. To eliminate the risk of oxygen entering the reactor it is supplied with inert gas to create overpressure and after pyrolysis the inert gas flow will carry the vapours out the reactor. To collect the pyrolysis oil, it is cooled down and captured, preferably in glass or stainless steel containers.

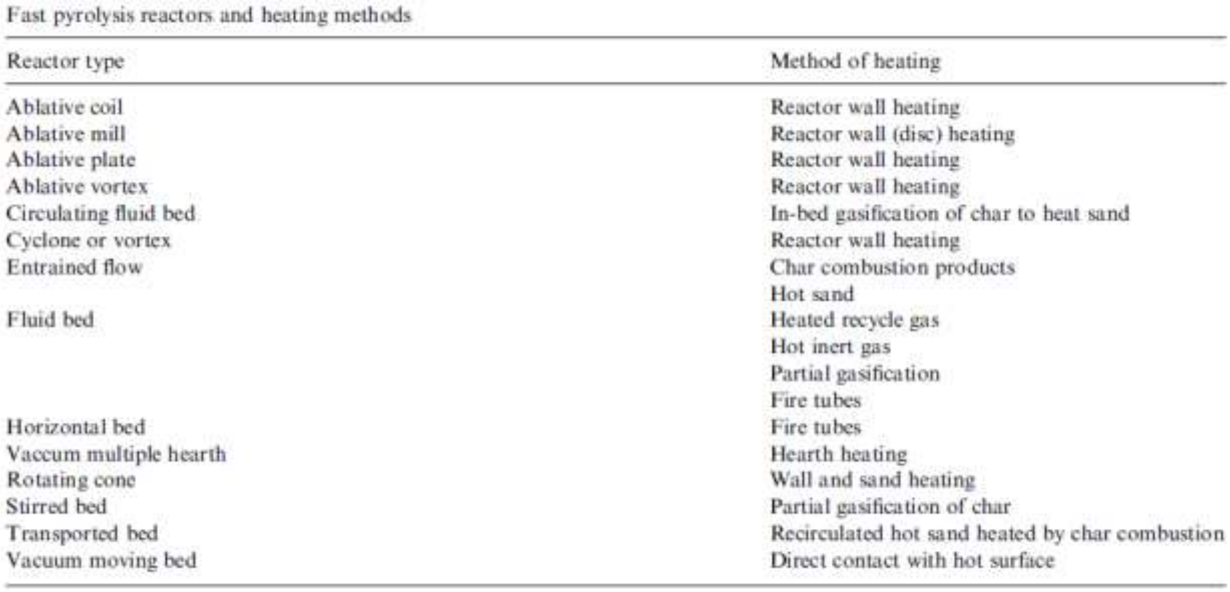
All these measures and improvements result in the technique known as fast pyrolysis.

1.3.3 Reactors

There are several types of fast pyrolysis reactors and countless variations. A way to classify the reactors is by their method of heat transfer. Conduction, convection and radiation are the three ways heat is transferred. In each case, it is a combination of the three different ways, with one or two methods taking care of the biggest share of heat transfer.

Table 4. Fast pyrolysis and heating methods

(Bridgwater, 1999)



Fast pyrolysis reactors and heating methods

Reactor type	Method of heating
Ablative coil	Reactor wall heating
Ablative mill	Reactor wall (disc) heating
Ablative plate	Reactor wall heating
Ablative vortex	Reactor wall heating
Circulating fluid bed	In-bed gasification of char to heat sand
Cyclone or vortex	Reactor wall heating
Entrained flow	Char combustion products
Fluid bed	Hot sand Heated recycle gas Hot inert gas Partial gasification Fire tubes
Horizontal bed	Fire tubes
Vaccum multiple hearth	Hearth heating
Rotating cone	Wall and sand heating
Stirred bed	Partial gasification of char
Transported bed	Recirculated hot sand heated by char combustion
Vacuum moving bed	Direct contact with hot surface

The reactor used in the experiments conducted is a bubbling fluidised bed reactor. It will be referred to as ‘fluidised bed reactor’ or shorter ‘reactor’. Other reactor principles could be used, but because of the specific focus and available reactor, the other techniques are not further discussed.

This division of fast pyrolysis reactors works on the main principles of heat conduction and convection; radiation is only a small factor. (Bridgwater, 1999)

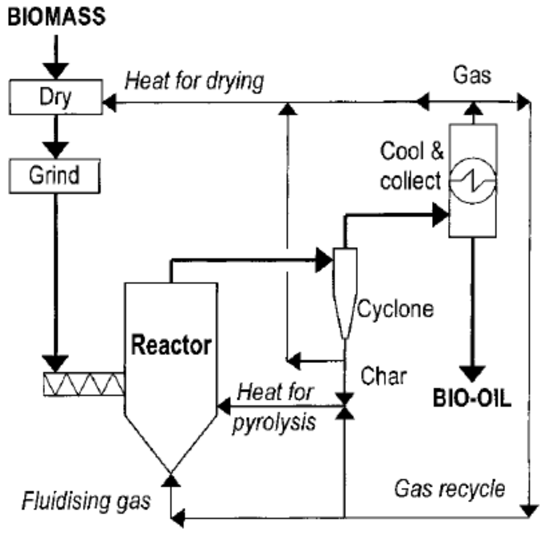


Figure 10. Basic layout of a Fast pyrolysis reactor

(Bridgwater, 2000)

Fluidised bed reactors are mostly circular and tube-like shaped. A main advantage of this construction is the construction strength and equal heat distribution. The heat is supplied externally by conduction. The reactor is fed with an inert gas supply to create an oxygen-free environment in the reactor chamber. The inert gas is also responsible for propelling and transporting the pyrolysis vapour through the reactor to the outlet with a connected cooling system. The fluid bed is a grain shaped 'sand' that allows conductive heat transfer and provides a surface for the biomass particles to be pyrolyzed up on by a combination of convection (preheated inert gas) and conduction. Most reactor beds are composed out of silica or quartz sands. Catalysts can be used to enhance reactor behaviour (Berdugo Vilches, 2016). The movement of the 'fluid' bed is critical for a uniformly distributed reaction in the particles. In this type of reactor, the biomass particles are fed or injected under inert atmosphere.

The temperature of the reactor needs to be controlled tightly to ensure a homogeneous production process. In most reactors, the char is removed with the passing inert gas and separated from the vapours by cyclone filtration. In most cases, there will always be a small amount of char remaining in the reactor, which needs removal after operation. A char removal system should be considered in continuous processes.

1.4 FPO, fuel for thought

After all the preparation and conditioning, the biomass is injected in to the reactor. The particles are almost instantly fragmented into three fractions: gases, liquids in vapour phase (oils) and char. The oil yield is dependant of many factors; moisture content in the feedstock, the type of raw material, reactor type/pyrolysis process, residence time and particle size. Fast pyrolysis oil is abbreviated as FPO.

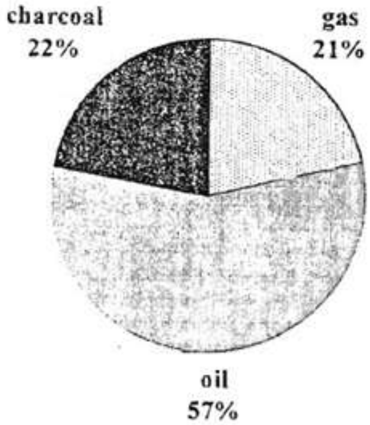


Figure 11. Fast pyrolysis yield

Yield (w.t%) of pyrolysis products of bamboo, (oil percentage is corrected by the wood moisture 7.37 wt.%, water content of oil is 18.69wt.%, reaction water 11.32 wt.%) (Meier, 1999)

Bio-oils are multicomponent mixtures comprised of different size molecules, derived primarily from depolymerisation and fragmentation reactions of three key biomasses building blocks: cellulose, hemicellulose, and lignin (Oasmaa, Fuel Oil Quality of Biomass Pyrolysis, 1999). The bio-oil obtained from the fast pyrolysis of biomass has high oxygen content. Ketones and aldehydes, carboxylic acids and esters, aliphatic and aromatic alcohols, and ethers have been detected in significant quantities. Because of the reactivity of oxygenated groups, the main problem of the oil is instability (Zhang, 2003).

Table 5. Chemical composition of bamboo and the derived FPO.

The left shows: the analysis of Moso bamboo. The table on the right displays the results of a detailed gas chromatography–mass spectrometry analysis of pyrolysis oil contents from the same Moso bamboo. (Yoshiaki, 2014)

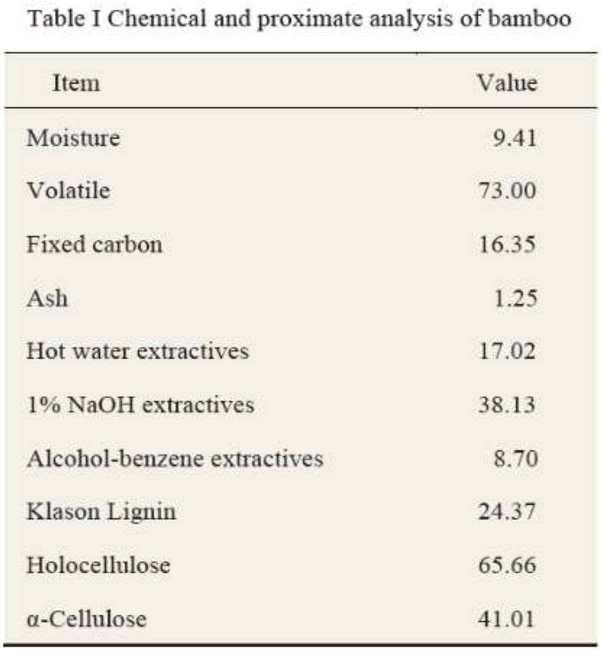


Table I Chemical and proximate analysis of bamboo

Item	Value
Moisture	9.41
Volatile	73.00
Fixed carbon	16.35
Ash	1.25
Hot water extractives	17.02
1% NaOH extractives	38.13
Alcohol-benzene extractives	8.70
Klason Lignin	24.37
Holocellulose	65.66
α-Cellulose	41.01

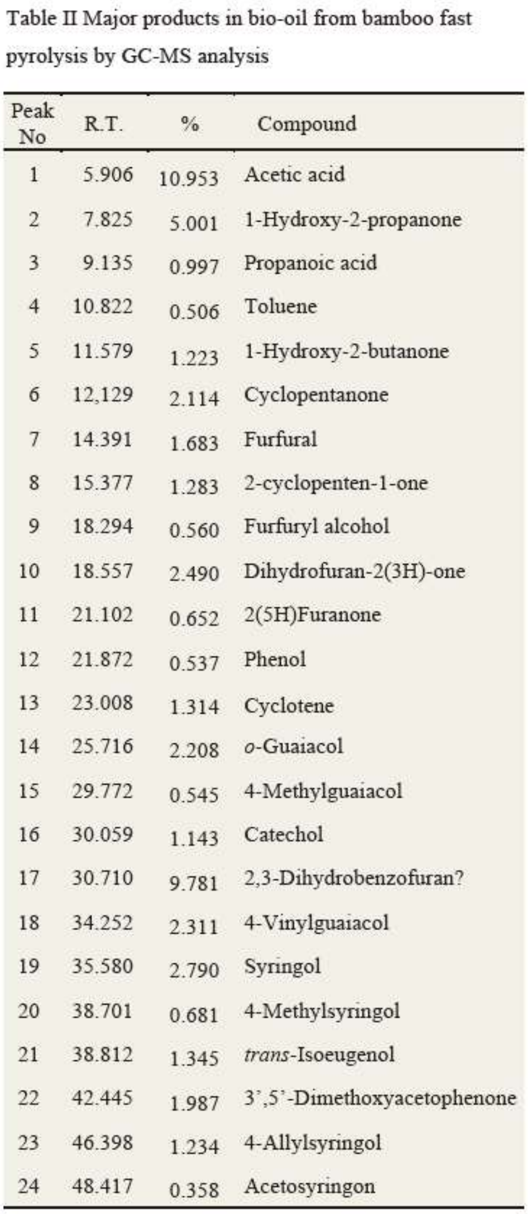


Table II Major products in bio-oil from bamboo fast pyrolysis by GC-MS analysis

Peak No	R.T.	%	Compound
1	5.906	10.953	Acetic acid
2	7.825	5.001	1-Hydroxy-2-propanone
3	9.135	0.997	Propanoic acid
4	10.822	0.506	Toluene
5	11.579	1.223	1-Hydroxy-2-butanone
6	12,129	2.114	Cyclopentanone
7	14.391	1.683	Furfural
8	15.377	1.283	2-cyclopenten-1-one
9	18.294	0.560	Furfuryl alcohol
10	18.557	2.490	Dihydrofuran-2(3H)-one
11	21.102	0.652	2(5H)Furanone
12	21.872	0.537	Phenol
13	23.008	1.314	Cyclotene
14	25.716	2.208	*o*-Guaiacol
15	29.772	0.545	4-Methylguaiacol
16	30.059	1.143	Catechol
17	30.710	9.781	2,3-Dihydrobenzofuran?
18	34.252	2.311	4-Vinylguaiacol
19	35.580	2.790	Syringol
20	38.701	0.681	4-Methylsyringol
21	38.812	1.345	*trans*-Isoeugenol
22	42.445	1.987	3',5'-Dimethoxyacetophenone
23	46.398	1.234	4-Allylsyringol
24	48.417	0.358	Acetosyringon

In contrast to diesel and gasoline, which are non-polar and do not absorb water, FPO is highly polar and can readily absorb water up to 35 wt.% (Demirbas, 2007). The oil is a homogenous hydrophilic (oleophobic) mixture of polar organics and water from both the pyrolysis reaction and the original water in the feedstock (Bridgwater, 1999).

Unlike mineral oils, fast pyrolysis bio-oils are non-flammable, non-distillable, possess only limited volatility, and ignite only at high temperatures (Diebold, 1997).

The reason for this is in the chemical composition of bio-oils. Bio-oils contain some light compounds (typically below 5 wt.%) that evaporate at near-ambient temperatures, and may cause a small short-duration flash in the presence of air and heat. These compounds include acetaldehyde (boiling point, bp 21 °C, flash point, fp -39 °C), furane (bp 31 °C, fp -69 °C), acetone (bp 56 °C, fp -17 °C), and methanol (bp 65 °C, fp 11 °C). However, the flash is rapidly suppressed by a large amount of evaporated water. With FPO's the low-boiling volatile compounds flash slightly before the evaporated water suppresses ignition (Oasmaa A. K., 2012).

1.4.1 Particles and water in FPO

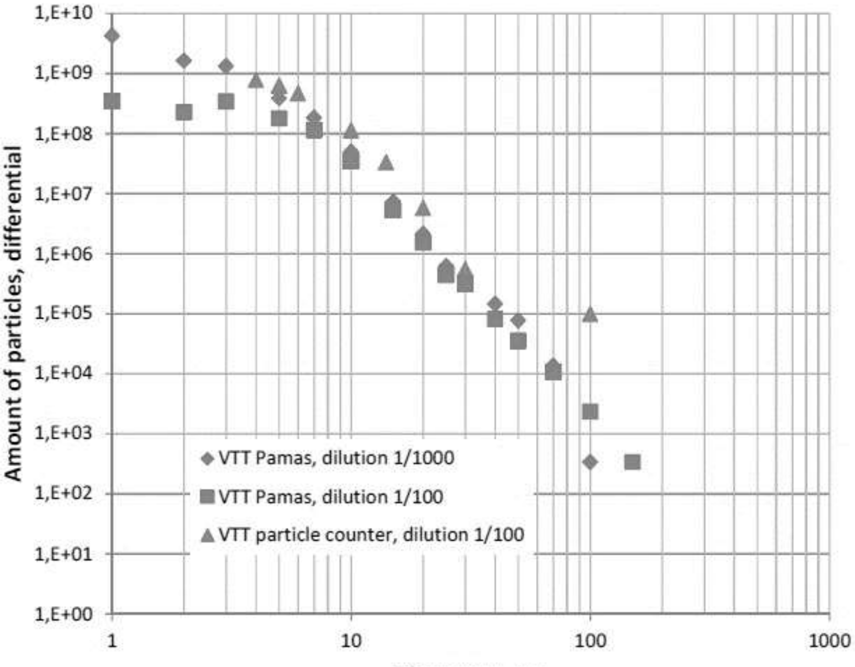


Figure 12. The particle size distribution for one fast pyrolysis bio-oil

The solids content is 0.33 wt.%, using two optical particle counters and two dilutions. (Lehto, 2013)

There are varying amounts of solids in fast pyrolysis bio-oils. Typical bio-oils contain less than 0.5 wt.% solids having an average particle size of approximately 5–10 µm, when cyclone(s) are used to remove the char from the hot vapours during pyrolysis (Lehto, 2013).

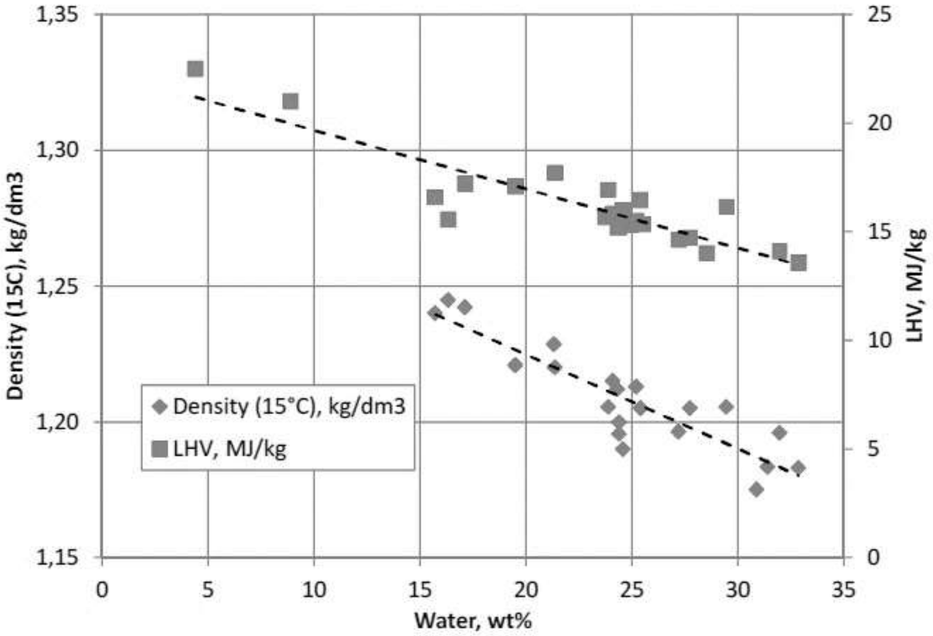


Figure 13. Density and heating value of pine and forest residue pyrolysis bio-oils.

Displaying the effect of water on FPO viscosity and heating value. (Lehto, 2013)

We can observe from Figure 13 that water has a positive influence on the density of FPO. However, extra water has a negative influence on the total heating value. An increase of 100% in water content, 15 to 30wt. %, results in a heating value loss of 9.37 (23,12-13.75) MJ/kg. The water content should be minimized as much as possible when conditioning biomass feedstock.

1.4.2 A clear overview of available FPO data

Table 6 provides a general overview of FPO characteristics distilled from four different articles. There are little to no differences between the reported values.

Table 6. FPO specifications by Larsen Priem

Sources: (Bridgwater, 1999) (Demirbas, Competitive liquid biofuels from biomass, 2010) (Lehto, 2013) (Czernik, 2004)

		FPO specifications by different publications				
Characteristics of fast Pyrolysis oils	Units	Bridgwater, 1999	Demirbas, 2010	Lehto, 2013	Czernik, 2004	General overview
Viscosity at 50°C	mm^2/s (cSt)				40 - 100	40 - 100
Viscosity at 40°C	mm^2/s (cSt)	30 - 200	25 - 1000	15 - 35		15 - 35
Pour point	°C	-23		-9 - 36		-9 - 36
Density at 15°C	kg/m^3			1100 - 1300		1100 - 1300
Specific gravity		1.2			1.2	1.2
Flash point	°C			40 - 110		NA
pH		2.5		2.0 - 3.0	2.5	2.0 - 3.0
LHV	MJ/kg			13	16	13 - 16
HHV	MJ/kg	17		18	19	18 -19
Solids	mass %			0.5	0.2 - 1	0.2 - 1
Ash	mass %	0.1	0.01 - 0.05	0.01 - 0.1	0.2	0.01 - 0.2
Sulphur	mass %	0.01	0.001 - 0.02	0.05		0.001 - 0.05
Carbon residue	mass %		0.001 - 0.02			0.001 - 0.02
Water content	mass %	25		20-30	15 - 30	15 -30
Water and sediments	volume %		0.01 - 0.04			0.01 - 0.04
Elemental composition						
C	mass %	56.4			54 - 58	54 – 56.4
H	mass %	6.2			5.5 - 7.0	5.5 - 7.0
O	mass %	37.1			35 - 40	35 - 40
N	mass %	0.2		0.4	0.2	0.2 - 0.4

1.4.3 Bunkering Fast pyrolysis oil: FPO vs HFO, MGO(DMA)

In table 7 FPO is compared to different types of bunker and transportation fuel. In general, the viscosity is lower compared to heavy bunker fuels (IFO380, 180), which means less auxiliary energy will be required to heat the fuel to injection temperature. The pour point on the other hand is almost the same. The sulphur content of the oil is very low, which is a competitive feature compared to the 3.5% sulphur IFO fuel.

Table 7. FPO compared with IFO 380. 180 and DMA

by Larsen Priem (Exxonmobile, 2017) (Lanka, 2017) (STEAUA, 2007)

		Petroleum based Fuels			
Specifications	Units	General specifications FPO	RMG 380 Exxonmobil	IFO 180 Lanka IOC	DMA STEAUA ROMANA
Viscosity at 50°C	mm²/s (cSt)	40 - 100	380	180	
Viscosity at 40°C	mm²/s (cSt)	15 - 35			1.5 - 6
Pour point	°C	-9 - 36	30	30	-6
Density at 15°C	kg/m³	1100 - 1300	991	991	860
Specific gravity		1,2			
Flash point	°C	NA	60	60	60
Acid number	mg KOH/g	-	2.5	2.5	0.5
pH		2.0 - 3.0			
LHV	MJ/kg	13 - 16	40		
HHV	MJ/kg	18 -19	42	40.6	43.1
Solids	mass %	0.2 - 1	0.1	0.1	
Ash	mass %	0.01 - 0.2	0.1	0.1	0.01
Sulphur	mass %	0.001 - 0.05	Max 3,5 IMO 2012		0.2
Carbon residue	mass %	0.001 - 0.02	18	15	0.2
Water content	mass %	15 -30	0.5	0.5	0
Water and sediments	volume %	0.01 - 0.04			

Although the gross caloric value of bio-oil per unit mass is only half of that of gasoline (usually around 44MJ/kg) the caloric value per unit volume approximately (20 to 26MJ/L) is almost 81% of gasoline (32MJ/L). (Garcia-Perez, 2010) The bigger density of the FPO does not compensate the difference in heating value. Compared to DMA (Maritime diesel) (43.1MJ/kg, 37MJ/l), the caloric value per volume FPO is respectively 70% of the equivalent DMA volume.

1.4.3.1 The CCAI for FPO

The calculated carbon aromaticity index (CCAI) is an index of the ignition quality of residual fuel oil. For spark-ignition engines the fuel has an octane rating. For diesel engines it depends on the type of fuel, for distillate fuels the cetane numbers are used. A pure theoretical example for FPO is made to compare both fuels on the petroleum field.

Formula for CCAI:

$$CCAI = D - 140.7\log(\log(V + 0.85)) - 80.6 - 210\ln(t + 273/323)$$

Where:
D= density at 15°C (kg/m^3)
V= viscosity (cSt)
t = viscosity temperature (°C)

Reference: The CCAI of RMG (HFO) 380 is 870 (Exxonmobile, 2017)

Example CCAI calculation for FPO

We take the FPO characteristics from table 7. FPO with a fuel density (D) of 1300 kg/m^3 at a temperature of 15°C. The kinematic viscosity for FPO is 35 cSt at 40°C. When fed into the formula they result in a CCAI of 1198.6.

1.4.4 Mixing FPO with diesel

FPO is a polar liquid as explained before. There has been many research on emulsification of FPO in petroleum derivate diesel. Up to today there has been no solution for this problem.

It is proven that FPO is miscible with bio diesel, but only in limited quantities and at high energy cost. In addition, extra chemical compounds are required. Bio diesel is generated from vegetable oils or animal fats and its polarity depends on the polarity of the resource it was derived from. The higher the lignin derived compounds, the lower the polarity of the bio-oil will be. A lower polarity bio-oil means; it will mix better with bio diesel.
(Garcia-Perez, 2010)

Baglioni et al (2001), at Pasquali Macchine Agricole (Italy) conducted a series of tests on emulsions of bio-oil in diesel fuel using a 6.25 kW single-cylinder engine Lombardini 6LD400. They could operate the engine using emulsions containing up to 50% bio-oil. They concluded that the main problems were deposits in equipment and erosion of the injectors. Chiaramonti et al. (2003), used bio-oil-diesel emulsions in four different engines and observed significant damage of the injectors and the fuel pumps, greater than that reported for pure bio-oil. It can be concluded that pure bio crude cannot be added directly to diesel, this does not mean FPO cannot be used in other solutions or with the correct modifications even pure, without any additive.

1.4.5 Conditioning FPO as diesel engine fuel

1.4.5.1 Hot filtration

Unlike mineral oils, fast pyrolysis bio-oils are non-flammable, non-distillable, possess only limited volatility, and ignite only at high temperatures. Hot-filtered bio-oils showed improved combustion characteristics (shorter ignition delay, shorter burn duration, less coking) mostly due to lower molecular weights resulting from vapor cracking during filtration and lower water content (Czernik, 2004). A wide spread application for hot filtration is thermal oil filtering, this technology is being highly developed over the last decade. Adding this step to the FPO production process will enhance the quality with a minimum extra energy and investment cost. The heating for this system can be provided separately, waste heat recovery is applicable. Practically this step is roughly an equivalent of the separator application used to treat HFO. It can be done on site or on board of a ship; units like in figure 14 are quite compact.

Figure 14 Liquid Process Systems, Inc. (LPSi) hot oil filtration unit,

from https://www.lps-filtration.com/hot-oil-filtration/

The most effective way is to place the oil filtration unit directly in series with the fuel supply system of the engine. An extra buffer tank with temperature control can supply the perfect pre-heat temperature to the engine fuel system. Combining the preheating with filtration saves even extra energy by improving oil quality with that same heat.

1.4.5.2 Preheating PFO

In contrast to heavy oil, which is typically preheated in the storage tank, bio-oil should be preheated in the fuel line just before combustion, due to its tendency to polymerize when exposed to moderate heat over a long period. Circulation of heated bio-oil back to the storage tank, requires control over the temperature in the tank and the lines.

Fast pyrolysis bio-oils contain high amount of energy in solid phase components and therefore filtering them away is not the primary target. The fuel system must be designed so that it will block or clog because of solid particle material deposition in filters and obstructions. Heavier grades of bio-oils must be heated up, to decrease their viscosity and enable proper atomization, still overheating must be avoided at all cost. Due to the instability of bio-oils, special care should be taken when using these liquids. Heating should be carried out indirectly with a low temperature surface. Direct heating can cause coking and polymerisation on the heating surface of the FPO heat exchanger. Temperatures between 40–80 °C are recommended for pumping, this will keep the viscosity low and reduce the rate of decomposition which increases with the rising temperature. Continuous recycling of FPO in a fuel oil system, leads to a significant deterioration in quality and increase in viscosity. Preheating of combustion air and mild preheating of bio-oil in the fuel line prior to injection are recommended (Lehto, 2013).

1.5 Practical tests with FPO

1.5.1 Pure FPO as fuel in a high-speed diesel engine

Shihadeh (1998), experimented with combustion of untreated fast pyrolysis oils in a single cylinder atmospheric diesel engine with compression ratio of 19.8 and running at 2400 rpm. He tested oils obtained by ENSYN (Ensyn Fuels Inc.) Rapid Thermal Process, and NREL (National Renewable Energy Laboratory) Ablative Vortex Pyrolysis. His research showed that the NREL oil was of higher quality being composed out of lighter components (lower molecular weight) and containing smaller amount of water (16.9 wt. % vs 26.3 wt. %). Never the less: little difference in the atomization characteristics and volatile species profile were found. During his operational tests both oils produced excessive amounts ignition delay, the engine could only be operated through pre-heating of the combustion air. The NREL oil preformed only a little better than the less qualitative ENSYN FPO, the water content was only partly responsible. The problem is not slow vaporization but slow chemistry. In normal petroleum based diesel combustion is predominantly mixing-controlled, while Shihadeh discovered that FPO combustion predominantly kinetically-controlled.

Even though Shihadeh (1998) could operate an engine on pure FPO, the performance was very low. By heating the air, the ideal combustion ratio changed and in direct relation the amount of fuel to be injected. Less fuel means less available chemical energy in the combustion to be converted into mechanical energy.

1.5.2 A balanced solution in medium speed diesel engines: Leech succeeds

A partial solution provided by Shihadeh (1998), was combustion air pre-heating. An additional solution to reduce the ignition delay is to reduce the engine speed and switch from high to medium speed engines. By reducing the rpm, the combustion stroke of the engine will be longer and the FPO will have more time to ignite. This choice implicates that the use of FPO is restricted to bigger industrial and maritime applications and excludes the use of FPO as a transportation fuel for road based vehicles which solely powered by high speed diesel engines.

An Omrod dual fuel engine was used to conduct tests with crude FPO (without any pre-treatment). Leech et al. (1997) succeeded in operating a dual fuel engine solely on FPO with pilot injection and combustion air preheating. These tests, which provide more than 400 running hours of practical evidence, can be considered a breakthrough. The Omrod engine is a six cylinder in line turbo powered diesel engine, generating 250kWe (e: Electrical generated power). Three of the six cylinder heads have been fitted with dual fuel injection capabilities. By starting the engine with up to 5% pilot diesel injection, combustion is initiated and the combustion chamber is brought to operational conditions. The once running the engine was successfully operated on FPO solely and running on three duel fuel cylinders only. After the test, black depositions were found on the pumps and injectors, these did not appear to affect the performance in any way. The exhaust emissions, except for CO, were below those obtained while running on petroleum derived diesel (Ormrod, (2000), Czernik, (2004)).
Tests at VTT Energy on an 84 kWe engine (high speed) and a 1.5 MWe (medium speed) Wärtsilä diesel engine showed that bio-oil could be efficiently used in pilot-ignited medium-speed diesel engines. The most important problems identified were difficulties in adjusting the injection system (excessive variability in composition of bio-oil), wear and corrosion of certain injection and pump elements (acids, particulates), and high CO emissions. However, these problems seem solvable (Solantausta, (1994), Gros, (1995), Czernik, (2004)).

1.5.3 Spicing the cocktail: blending of FPO with bio methanol and or ethanol to improve combustion characteristics.

Previous solutions to counter the ignition delay involved adaptions to the engine and combustion air pre-heating. The solution may be lying in the fuel composition. The use of pure FPO alone might be too difficult. Just like in conventional diesel and gasoline additives can be used. For diesel fuels cetane enhancers are added to the fuel. A better cetane rating in diesel means the fuel ignites quicker in the cylinder (Bjornstad, 2014).

A diesel engine has no electrical ignition and relies on the unaided auto-combustion of the injected diesel. Older diesel engines had problems with this because of the lower compression ratios, poor injector performance, lower injection pressures and lower cylinder temperatures. Swirl chambers and pre-combustion provided the solution, but reducing power output and engine performance.

The most common cetane improvement chemicals are extremely combustible at the high temperatures found in the combustion chamber. They will start burning more quickly than the heavier components of the fuel (Bjornstad, 2014). Once the ignition is started the energy released will put a chain reaction in motion. This energy, that is introduced into the cylinder is a form of pre-ignition. This chain reaction will consume downwards in ignition quality up to the point where the required ignition energy for the FPO is present and the combustion peak is reached. Our polar FPO is miscible with bio alcohols and methanol, which can be used as cetane enhancer.

In 1993 at VTT Energy, Solantausta et al. used a 500 cm^3 high-speed, single cylinder, direct injection Petter diesel engine with a compression ratio of 15.3:1 and a maximum power development of 4.8 kW for a test on FPO. It could not achieve autoignition of bio-oil without additives. A minimum of 5 vol. % of a nitrated alcohol (cetane enhancer) was required to achieve stable engine operation. Typically, 0.1-1 vol. % of this component is added to standard diesel fuels for optimal performance. Even with 9% of this additive, the ignition delay for bio-oil was 9 CAD (crank angle degrees), compared to 6 CAD for No. 2 fuel oil (distillate fuel comparable to transportation diesel). In addition, coke formed during bio-oil combustion, resulting in rapid clogging of injection nozzles. CO, NO_x, and hydrocarbon emissions. These were measured after the catalytic converter, the exhaust analysis from pyrolysis oil was comparable to those from diesel fuels (Czernik, 2004).

Suppes at University of Kansas found that ignition delay of a hot-filtered bio-oil (no particles) measured in a combustion bomb was like that of 27 Cetane reference fuel. His tests on a blend of 72% pyrolysis oil, 24% methanol, and 4% cetane enhancer (tetraethyleneglycol dinitrate) tested in a single-cylinder, air-cooled Lister Petter diesel engine showed the same performance as for diesel oil. The study concluded that the application of pure pyrolysis oils should be limited to low-speed diesel engines with relatively high compression ratios, blends of biomass oil and methanol could be used in high-speed engines, especially with cetane-improving additives. (Czernik, 2004), (Shihadeh, 1998)

1.6 FPO conversion to transportation fuels

As concluded in the previous chapter, FPO is not directly suitable as transportation fuel for high speed diesel engines. Development of conversion techniques has led to three major options.

1.6.1 Catalytic cracking

This is the successor of thermal cracking in the oil industry; the technique is used to break up the long chains of hydrocarbon molecules into lighter and shorter strains. By adding a catalyst to the cracker chamber the temperature and pressure can be reduced, because of the active function of the catalyst. Basically, it removes hydrogen atoms from the alkanes and leaves the carbon atom with a positive charge. Reorganisation of these atoms lead to new bonds and equivalent products. Modern cracking uses zeolites as the catalyst. These are complex aluminosilicates, and are large lattices of aluminium, silicon and oxygen atoms carrying a negative charge (Clark, 2015).

The pyrolysis oil obtained either by non-catalytic or catalytic route contains higher oxygen content (∼40% with non-catalytic and ∼22% with catalytic) in the form of aliphatic and aromatic oxygenates. It is very much essential to upgrade pyrolysis oil further either by hydrodeoxygenation or zeolite cracking (fluid catalytic cracking) route (Wildschut, 2009).

1.6.2 Hydrotreating and hydrogenation:

Hydroprocessing is carried out in fixed-bed reactors at high pressures, with the severity of the reaction conditions generally increasing with the heaviness of the feed. Reactors used with the heavier feeds are trickle beds, in which the liquid oil trickles through the catalyst bed, with hydrogen concentrated in the gas phase. Slurry reactors have also been used for heavy feedstock. When a catalyst is introduced into this process the aims shifts slightly and the primary objective catalytic partial hydrodeoxygenation is to increase the energetic value of the oil by removing bound oxygen in the form of water. Hydrodeoxygenation of bio-oils involves treating the oils at moderate temperatures with high-pressure hydrogen in the presence of heterogeneous catalysts.

The process was carried out in two distinct stages, a first stage at relatively low temperatures (525–575 K), aimed to stabilize the bio-oil and a second stage at higher temperatures (575–675 K) to de-oxygenate the intermediate product (de la Puente, 1999).

This technique is a proven and reliable way of upgrading oil products. It comes at a high price; the introduction of high amounts of hydrogen under pressure is very costly, when compared to the energy gain that is obtained.

1.6.3 Catalytic pyrolysis

Introduction of a catalyst into the pyrolysis reaction, mostly in the form of powder in fluidised bed reactors, has the goal of deriving FPO products with the desired characteristics for combustion and a chemical stability.
Huber and Corma (2007) describe that removing oxygen from the compounds in the fast pyrolysis reaction in forms of CO, CO_2 or H_2O during catalytic cracking. This process also generates undesirable by products in the form of acids and coke.

Yorgun et all. (2008), tested the introduction of activated alumina (Al_2O_3) as a catalyst into a static pyrolysis reaction under controlled nitrogen atmosphere. The catalyst does not lower the FPO production yield. On the other hand, but neither had any direct effect on the general composition of the FPO. Analysis by column chromatography showed that the aliphatic and aromatic hydrocarbon content is observably higher than in the control sample without catalyst introduction. By increasing these compounds the suitability of FPO as a transportation fuel is increased.

French et. all. (2010), experimented with the use of zeolite catalyst. They state that; Catalytic upgrading of pyrolysis vapours using zeolites is a potentially promising method for removing oxygen from organic compounds and converting them to hydrocarbons. In the presence of catalysts, the volatiles released by pyrolysis underwent various reactions: deoxygenation, dehydration, decarboxylation, decarbonylation. This resulted in the production of hydrocarbons and in additional carbonaceous solids (coke). In general, they concluded that higher coke production could be observed in the catalyst operated reactor. This increase on the other hand, results in greater yields of hydrocarbons, which is related to the extra dehydration activity initiated by the catalyst. However, lignin-derived vapours produced less coke than those from cellulose and wood pyrolysis the total number of solids (char and coke) could reach 30–60% of the feedstock. The highest yields of hydrocarbons from wood,16wt.% including 3.5wt.% of toluene were obtained for the laboratory prepared nickel-substituted ZSM-5 zeolite though a few other laboratory-prepared catalysts and a commercial catalyst (Zeolyst 8014) performed almost as well. Tests with Semi-continuous operation of the pyrolysis/vapor cracking process using a fixed bed of a ZSM-5 catalyst at 500°C and a WHSV (weight hour space velocity: mass flow rate vs catalyst mass present in the reactor) of 4 showed good deoxygenation performance for up to 4 min. At the end of this test period the catalyst was partly deactivated and required regeneration to maintain high activity.

The use of catalysts to enhance and deoxygenate FPO shows much promise. However, using these catalysts results in the presence of catalytic fines in FPO. These have an erosive impact on fuel injection systems and cylinder liners. Erosion of expensive high precision injectors is a characteristic that must be taken into consideration when fuel application in diesel engines is considered. One of the main reported problems is the scoring of the piston liner by catalytic fines. This will damage the honing marks of the piston and disrupt optimal lubrication flow between the liner and the piston, causing extreme wear to the segments up to destroying them completely (Mfame, 2015).

This brings us to the dilemma, that FPO's are free of catalytic fines, and this is a big advantage compared to the catalyst rich residual fuels obtained from petroleum.
Modern IFO 380 provided by ExxonMobil refineries contain: 350mg/kg vanadium, 100mg/kg sodium and 60 mg/kg combined residue of aluminium and silicon (Exxonmobile, 2017).

1.6.4 FPO Emissions and Sulphur

The emissions of bio-oil combustion are situated between those of light oil and the lightest heavy oil, but particulate emissions might be higher. It is very important to note, that there are practically no (very little) SOx-emissions produced by FPO combustion (Oasmaa, 2001).

Concluded from table 6, FPO is a very acid oil, yet because of the composition of these acids no readily visible impact on the emissions is observed, because of the absence of sulphur.

The IMO declared that: ships trading in designated emission control areas should use on board fuel oil with a sulphur content of no more than 0.10% from 1 January 2015, against the limit of 1.00% in effect up until 31 December 2014. (IMO, 2014)
MEPC 70 (October 2016) considered an assessment of fuel oil availability to inform the decision to be taken by the Parties to MARPOL Annex VI, and decided that the fuel oil standard (0.50% m/m) shall become effective on 1 January 2020 (resolution MEPC.280(70)). (IMO, 2017)
General sulphur content of FPO ranges from 0.001 to 0.05% wt.%. FPO is a suitable alternative when considering the use of low sulphur fuel. One of the main advantages over de-sulphured fuel-oils is that there is little additional (waste) sulphur produced during the fast pyrolysis process.

Naturally, the emissions from pyrolysis oil combustion are very dependent on the original levels of solids, metals, water and nitrogen in the oil being combusted. The produced NO_x-emission is mainly due to the conversion of fuel-bound nitrogen, as the lower flame temperature of pyrolysis oil combustion reduces the production of thermal-NO_x. However, total-NO_x content is the combination of those oxides produced by thermal and fuel bound nitrogen mechanisms (Shaddix, (1999), Tzanetakis,(2010)). To reduce the NO_x-emissions without refining the fuel, the use of staged combustion and EGR are alternative and can be recommended.

CO emissions reported by Leech (1997) and Ormrod (2000) form practical tests in diesel engines were reported to be little larger than for petroleum derivate diesel combustion.

Solid particle emissions from bio-oil combustion tests show big variations between obtained results. That is mainly due to several kinds of oils used. Particulate emissions are in relation with the number of incombustible solids in the bio-oil. To counter this problem, reduce the solids content of the bio-oil to < 0.1 wt.%. Separate and filter out the inorganic components in the form of ash and sand originating from the feedstock. The particles are typically very small (< 10 µm) and the amount of unburnt in solids is low (Oasmaa, 2005).

There is not much published data available for VOC (Volatile Organic Compounds) and PAH (poly aromatic hydrocarbons) emissions or other analysis of the flue gas. Both tar and PAH have been measured from various pyrolysis oils. By introduction of new techniques, the values for tar have been decreased from about 3 mg/MJ to under the detection limit of the system while PAHs from 1000 microgram/MJ to under 12 microgram/MJ (Gust, 2004).

NO_x-measurements were completed for two pyrolysis oils. Both produced by the same process but differing in fuel nitrogen content. The combustion data indicated that fuel nitrogen conversion efficiency increases with increasing oxygen concentration if flame temperature is held constant, fuel nitrogen conversion efficiencies decrease with increasing fuel nitrogen content (NO levels increase, conversion efficiencies decrease), and NOx-emissions are dominated by NO, which is primarily formed from fuel nitrogen (Baxter 1995, Lehto 2013).

1.6.5 Lubrication of engines running on FPO

Stated by Briens and Chiaramonti: The high acidity, low thermal stability, low calorific value, high viscosity and poor lubrication quality are some of the properties limiting the direct use of FPO as transportation fuel (Briens, 2008, Chiaramonti, 2007).

It is not that FPO has no lubricating qualities, they are reported to be lower than required of modern diesel fuels. This is partly caused by the absence of sulphur, which enhances lubrication quality, and the high amount of water in the FPO.

A similar problem was experienced in the USA when the switch was made to ultra-low sulphur diesel. With the use of bulk lubricity agents, the right lubrication oil (additives) and possible adaptions to the lubrication system, this problem can be countered (Bjornstad, 2014).

1.7 Energy and economics of FPO

At present moment, the cost of pyrolysis oil compared to other petroleum and gas resources is too high to be profitable in the current economical mindset. If the mindset would shift to a more renewal orientated policy and or the petrol and gas resources would dwindle in availability it becomes an interesting power source. It is also a fuel source that allows the use of conventional combustion powered machinery, complete independence of oil producing countries and companies. It only requires the availability of a suitable climate and farm land to grow energy crops. Another option is a steady input of biomass that is considered waste by other parties. Figure 15 shows the energy balance of a fast pyrolysis process with *Miscanthus × giganteus* (elephant grass) as biomass feed stock.

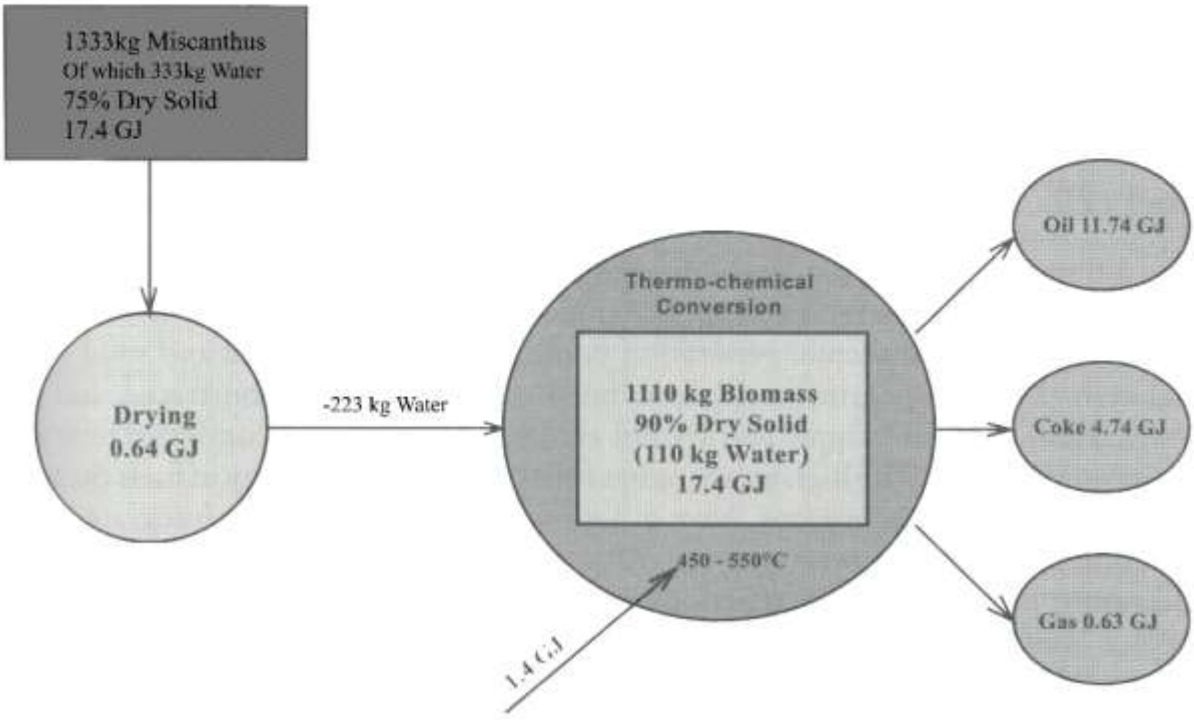


Figure 15. Energy balance of Miscanthus × giganteus *biomass conversion.*

Using fast pyrolysis with preconversion drying (El Bassam, 1998) (Shakir, 1996)

1.7.1 Fuelling a ship with FPO

To illustrate the economic aspect of FPO production following calculation was made:

How much hectares of crop do you need to produce enough FPO for the operation of a post Panamax plus sized (7,000-8,000 TEU) (MMD, 2017) container ship for a voyage between the port of Madras and the port of Antwerp (7014.14NM) (SeaRates, 2017) at a slow steaming speed of 18 knots? The distance is respectively covered in 24 days, with an average HFO consumption of 75t/day (Dagkinis, 2015). HFO has an average heating value of 42 GJ/t (Exxonmobile, 2017) and FPO a heating value of 18 GJ/t (Lehto, 2013). The ship is powered by an adapted dual fuel engine with 5% bio diesel pilot injection (Leech, 1997). The feedstock for the pilot injection fuel is canola (*Brassicaceae* family) derived bio-diesel, up to 40% of the weight of the harvested seeds is oil. The annual processed yield of one hectare in Canada, seeded three times a year is 3.18 t/ha bio diesel (Clayton, 2000). The FPO is produced by a theoretically scaled-up version of the process as demonstrated by de Wild (2015). The pyrolysis process uses *Bambusa vulgaris* as feedstock. It produces 0.476t FPO, 0.307t char and 0.247t gases per ton bamboo. The bamboo is grown in India with a reported annual yield of 35.64t/ha from a 10-year-old plantation (SEBI, 2017). The ship makes twelve one-way voyages a year.

Calculation

24 sailing days multiplied by a consumption of 75 t/day is 1800 t HFO. The amount of HFO bunkers multiplied by the heating value of 42GJ/t results in the total required amount of energy is 75600 GJ.

To convert the consumption from HFO to FPO we divide the total required amount of energy by the heating value of FPO (18GJ/t), resulting in 4200t -5% pilot fuel= 3990t FPO and 210t bio-diesel.

To calculate the production of FPO we multiply the reactor yield per ton bamboo resulting in 0.4284t FPO per ton bamboo (0.476t-10% losses from hot filtration) (Czernik, 2004) multiplied with the FPO heating value (18GJ/t), obtains a FPO energy yield of 7.7112 GJ/t bamboo.

To calculate FPO energy yield per ton bamboo we multiply the amount of required fuel with the heating value of FPO and hereafter we divide it by the FPO energy yield, resulting in (9313.725t) the required amount of raw bamboo for one voyage. Calculating the required amount of agricultural land for that amount is done by multiplying it with the annual yield of a hectare bamboo (*Bambusa vulgaris*) in India (35.64t/ha) resulting in an area of 261.327ha farm land per voyage.

The pilot fuel is bio diesel derived from canola. We divide the amount of bio diesel (tons) by the annual canola bio diesel yield per ha by, resulting in 66.03 ha per voyage.

Overview

Table 8. Overview calculations

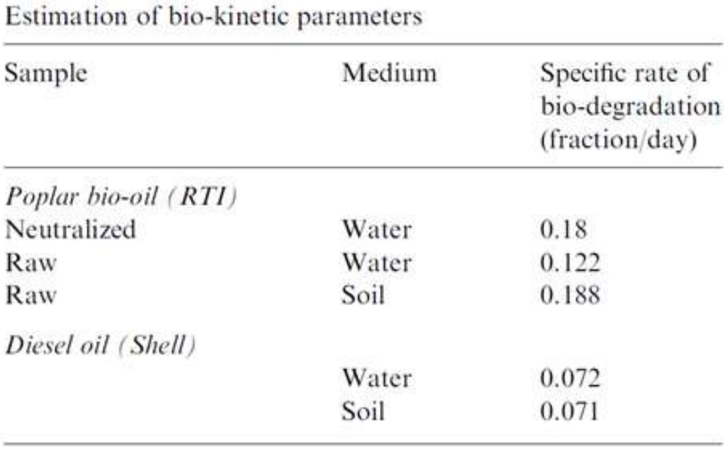
The resource cost to sail a ship between Madras and the Port of Antwerp on FPO is displayed for a single voyage (left) and 12 voyages (right). by Larsen Priem

Requirements	1 Voyage	1 year (12Voyages)
Amount of Fuel (t)		
FPO	3990	47880
Bio diesel	210	2520
Biomass (t)		
Bamboo	9314	111768
Canola	525	6299
Farmland (ha)		
Bamboo	261	3136
Canola	66	793

1.8 Bio Degradation of FPO

Table 9. Bio-degradation of bio-oil compared to diesel oil

(Rozich, 1992)



Estimation of bio-kinetic parameters

Sample	Medium	Specific rate of bio-degradation (fraction/day)
Poplar bio-oil (RTI)		
Neutralized	Water	0.18
Raw	Water	0.122
Raw	Soil	0.188
Diesel oil (Shell)		
	Water	0.072
	Soil	0.071

Rozich (1992) stated that:

- Respirometry is a suitable technique for assessment of the degradation behaviour of bio-oils in natural environments.
- Pyrolysis bio-oils biodegrade aerobically at a substantially higher rate than hydrocarbon fuels like diesel oil.
- pH neutralisation of bio-oil enhances its biodegradability

Bio-oil does not appear to be a significant environmental hazard even in raw form.

Biodegradability is enhanced by neutralisation with bases like lime.

Table 9 shows that even the FPO in water is degraded almost 72% faster than diesel oil. This is a positive characteristic compared to petroleum and crude oils.

2 Equipment and Methodology

2.1 Reactor layout and parts

1 Fluidised bed reactor

1.1 Gas supply connection (inlet)

1.2 Temperature sensor

1.3 catalytic fluid bed

1.4 Electrical heating coils

1.5 Reactor head

1.6 Feed valve

1.7 Load valve

1.8 service air connection

1.9 3/2 injection control valve

1.10 Injection piston

1.11 Inert gas valve

1.12 Reactor exhaust pipe (outlet)

1.13 Cyclone filter outlet to cooler

1.14 Cyclone filter housing

1.15 Filter deposit

2 Preheater

2.1 Inert gas supply connection preheater (inlet)

2.2 Preheater head

2.3 Preheater outlet connection

2.5 Connection pipe Reactor- Preheater

3 Tube reactor

3.1 Ventilator

3.2 Reactor screw lid

3.3 Reactor exhaust connection

3.4 Temperature sensor

3.5 Electrical heating coils

3.6 Inert gas supply connection (inlet)

4 Control box

4.1 Power supply cord

5 Float gauge meters with flow control

5.1 Main inert gas supply connection (inlet)

5.2 Flow control valves

5.3 Small diameter inert gas supply valve

5.4 Small diameter inert gas connection

5.5 Main inert gas supply pipe

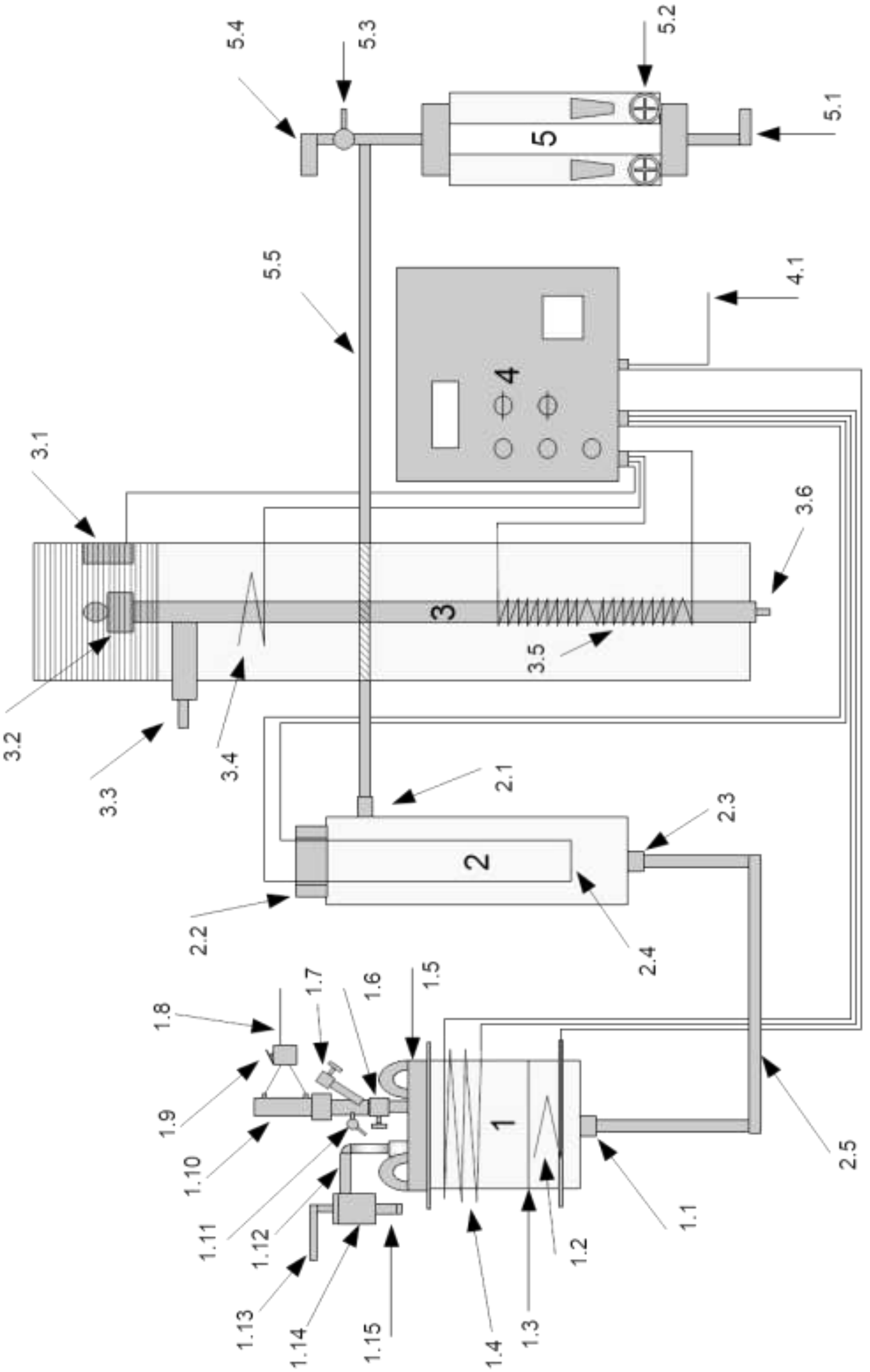


Figure 16. Reactor overview with numbered components

by Larsen Priem

2.1.1 Electrical layout

2.1.1.1 Current measurement

The electrical circuit of the reactor is situated in the control box on the reactor module. The reactor module is fed by 230V AC grid power. To determine the current through the operational reactor, a simple current measurement was carried out. To obtain the actual active power consumption a power measurement circuit was constructed in the power line feeding the reactor. Figure 16 is the electric schematic of the connections in the control box of the reactor.

Following values were obtained:

Table 10. Current measurements and calculated resistive power

by Larsen Priem

	Max current (A)	Calculated resistive power (kW)
Free standing non-operational control system	0.034	0.078
Preheating system	4	0.92
Main heating system	8.4	1.932
Full operational system	12.7	2.93

2.1.1.2 Power measurement

Table 11. Power measurement

by Larsen Priem

	Max current (A)
Free standing non-operational control system	0.034
Preheating system	4
Main heating system	8.4
Full operational system	12.7
*The precision of the measurement is too low to detect this minimal consumption	

The difference between the actual power measured and the calculated amount of resistive power can be explained by the fact that the heating coils are not purely resistive consumers. Like their name already suggests they are coils.

If we calculate the amount of reactive power and the power angle, we obtain following values:

P=2.85 kW S=2.93 kW (Table 11 and 12)

Q=Root (S^2 - P^2) = 0.68 kW

phi= cos^-1(P/S) = 13.42° power angle= 0.97

The reactor coils cause only a minimal phase shift.

Construction of the electrical circuit

The electrical circuit is composed out of two main components: preheater and main heating. Three power levels feed the connected components, respectively 230V AC, 24V DC and 12V DC.

2.1.1.3 Preheater

This circuit is the simplest of the two and is not under influence of the Omron controller. The circuit is responsible for the preheating (by convection) of the inert gas prior to its introduction in the reactor. The preheater is activated 30 seconds (up to 1 minute maximum) before the biomass is injected in the preheater, to maximize the speed of the pyrolysis reaction. It is not controlled and thus directly operates at 100% power. To minimize the thermal stress and fire danger the preheater circuit may only be operated for continuous period of 3 minutes. If the preheater is operated for a longer period, switch it off and wait for the reactor temperature to settle again to the set point temperature.

The circuit exists out of the heating coils, of which only one is connected, the power relay, Omron control relay, the signal light, the alarm light and the preheater switch. The switch activates the power relay which on its turn connects the power to the heating coil in the preheater. The Omron relay functions as a voltage detector, its power supply is connected in parallel with the power relay and will activate the alarm light if no power is detected on the input of the power relay.

2.1.1.4 Main heating

This circuit is responsible for the main heating of the fluidised bed reactor through conduction by an electrical heating coil. This circuit is controlled by an Omron E5CN-H proportional controller (used as on-off controller). Operational procedures can be found in the manual.

The on-off control is obtained by periodically switching the power supply on and off, there is no gradual control. Such operation, is characterized by very fast and frequent switching of the power source. The use of a convectional magnetic relay is not practical. The fast and frequent operation would wear down a conventional relay and its mechanical components in no time.

The Siemens Sirius, an electronic relay is used to solve this problem. This component has no moving components that are prone to wear, it operates purely electronic and can switch up to several times a second.

Operating an electronic relay at high frequency generates heat, to dissipate this heat the relay is mounted on a bigger aluminium plate. By increasing the surface, the heat can dissipate faster and more easily.

$$Q = k * A(T2 - T1) * t/d$$

Q (Joule) is the amount of energy dissipated over the time t(seconds), A (m^2) is the surface of the plate and d (m) the thickness. T2 (Kelvin) is the temperature of the heated element, while T1 (kelvin) is the cold reservoir. The thermal conductivity of the material is represented by the k factor(Watts/meter*Kelvin).

The plate dissipates the heat through convection:

$$Q = Hc * A * (T2 - T1) * t$$

Q (Joule) is the amount of energy dissipated over the time t(seconds), A (m^2) is the surface of the plate. The heat transfer through a gas is represented by Hc; the heat transfer coefficient (Watts/m^2*Kelvin)

The Omron controller is provided with a live temperature signal of the fluidised bed reactor. A thermocouple supplies the controller with an analogue temperature dependent voltage. The main heating circuit is unable to operate if the Omron relay receives no power on its input, if there is power supply on the main rail, but not on the circuit the alarm light will indicate this.

2.1.1.5 On-off control

The circuit consists out of: the heating coil, Omron controller, electronic relay, signal light and the main heating switch.

The controller switches the heating supply between a programmed band of (set to 5°C)

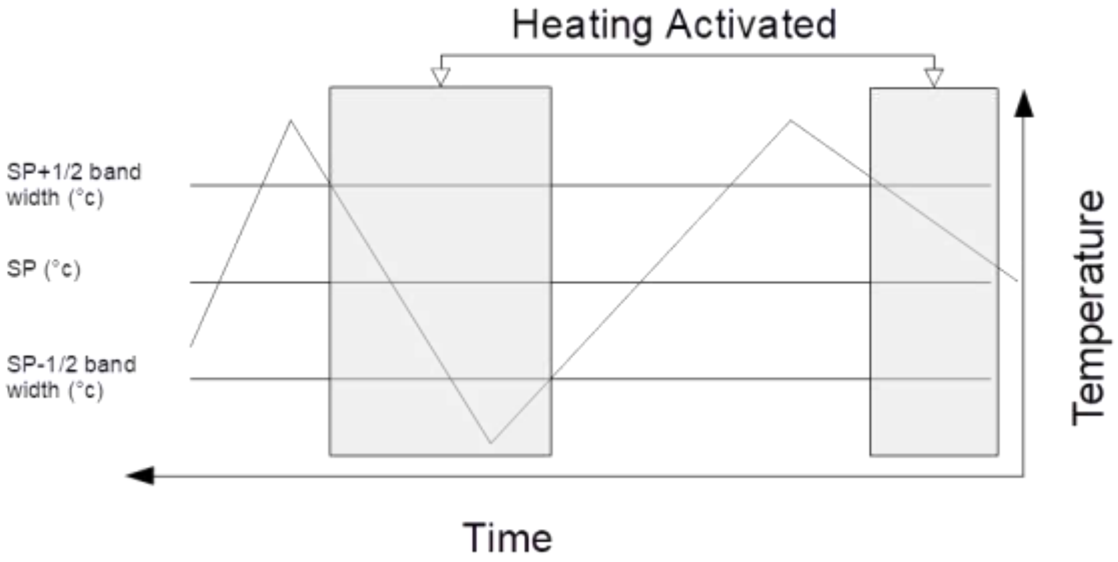


Figure 17. The behaviour of the on-off controller.

The trend line represents the variation in temperature, while the boxed areas display the operational time of the heating. The horizontal lines represent the set point and parallel to it, the operational band. These values are determined by the settings of the controller. The state of the controller (on or off) changes when the temperature reaches the extend of the operational band. by Larsen Priem

2.1.1.6 Switching to the Tube reactor with Carel controller

Switching to the Tube reactor with Carel controller is done by switching the input of the Sirius relay from the Omron relay to the Carel controller. The power supply (12V DC) of the Omron controller is shifted to the Carel controller. The heating coil supply cable to the Sirius relay must be exchanged: the fluidized bed heating coil cable is changed with the cable supplying the tube reactor’s heating coil. The preheater circuit must be detached and isolated when operating the tube reactor.

The electrical schematic in figure 18 is based on the current cabling and connections in the control box, for the operation of the fluidized bed reactor through the Omron controller.

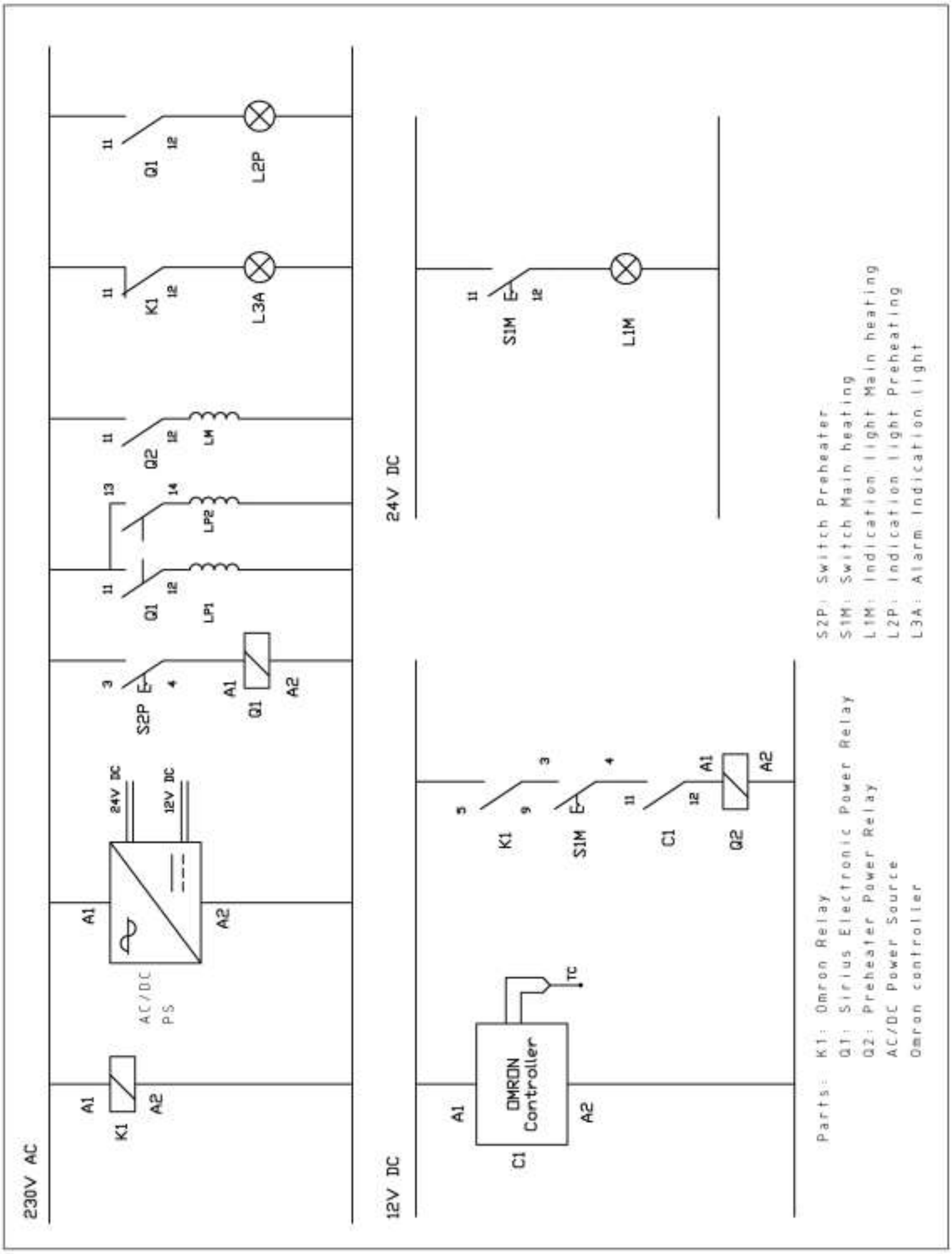


Figure 18. Electrical schematic of the circuit in the reactor control box

by Larsen Priem

2.2 Evaluation of the reactor

At the start of the project, the condition of the pyrolysis reactor evaluated. This included a full inspection of the installation.

All connections where disassembled and all piping was cleaned. The silica sand that makes up the fluidised bed of the reactor was in clean condition and of sufficient level. The control box was checked and the power-relays that control the heating coils of the reactor were tested. The controller was booted and ran through an operational check.

After the evaluation following conclusion was made:

A. The reactor’s electrical control module and connections to the heating needed to be adjusted and repaired. The loose wires inside the control box needed to be insulated and tagged;

B. The indicator light of the main heating was broken;

C. A section of the ceramic bead insulation of the main reactor heating coil was missing, this section and all the broken beads on the coil needed replacing;

D. A better and safer biomass injection system was required;

E. The reactor and preheater needed to be isolated by non-flammable insulation;

F. The preheater was wrongly attached (welded straight) to the frame and bended by thermal stress;

G. The reactor was very unhandy to move, wheels needed to be installed;

H. The reactor needed to be tested in trials to determine proper operational procedures;

I. To reduce the ash content of the final product a cyclone filter in the output flow is needed;

J. An oil recovery system was needed to re-liquefy the gases produced by the reactor.

2.2.1 Reactor development

2.2.1.1 After the evaluation following objectives were carried out:

A. The reactor’s electrical control module and connections to the heating needed to be adjusted and repaired. The loose wires inside the control box needed to be insulated and tagged;

During inspection of the control box many badly connected wires were discovered. These were fitted with new cable shoes and properly reconnected. Some wires were unattached and needed to be reconnected to ensure proper operation of the reactor module.

The fact that only one reactor can be operated at the same time means that connections need to be switched, resulting in loose wires inside the control box. In this case the tube reactor was disconnected and the system is lined up for the operational use of the fluidised bed reactor. The loose wires were insulated to prevent them from forming false connections or create shore circuits. They were all tagged with labels indicating their purpose. The Carel controller is disconnected but can be reconnected.

B. The indicator light of the main heating was broken;

The light bulb inside the main heating was broken and needed replacement. The bulb inside the socked was a 230V AC bulb, but the light was connected to a 24V DC supply. This was probably overlooked when the second reactor was installed and the connections were switched to the new controller.

C. A section of ceramic bead insulation of the main reactor heating coil was missing, this section and all the broken beads on the coil needed replacing;

Th heating coil of the reactor was removed and the ceramic insulation was inspected. It was in terrible condition. Around 20 cm of insulation beads was missing and a total amount of 15 cm beads were damaged.

Due to embrittlement, caused by the extreme temperatures the ceramic insulation beads on the main heating became porous and became prone to crack. Some beads were reduced to no more than mere fragments and other were missing completely. This insulation is the only barrier between the frame and the power source. When this barrier is breached and the coil touches the frame, the frame will become electrically charged and there is a major chance of an electric shock.

The missing and broken beads were replaced with ceramic beads of the same dimensions and a heat resistance up to 1300°C.

During the first productive test run on pine wood, the insulation of the electric cables supplying the preheater, melted because of the excessive heat on top of the insulated preheater. The insulation on these wires was replaced by ceramic beads to ensure continuous operation in extreme conditions.

During the second productive test run on pine wood, the frame of the reactor became electrically charged near the end of the test. The isolation of the main heating circuit was compromised. This happened because the use of two different kinds of ceramic beads that didn’t close completely when they meet. The whole insulation of the heating coil was replaced by new beads. During the replacing, the coil broke in to two sections. It was welded back together with a TIG welding machine, this without the addition of extra material.

D. A new biomass injection system was required;

The biomass injection system that was supplied with the reactor was inefficient, time consuming and very dangerous to use. We will refer to it as mark I. The Mark I injection system used an injection pipe-gun with inert gas propellant. It consists out of two main parts and a hose to supply the inert gas. The two main pieces are connected by a hose coupling that functions as a loading chamber. The injection pipe-gun is connected by a hose to the small diameter inert gas supply valve. It has two valves: gas supply valve and an injection valve. On the reactor head a feed-valve connected to the reactor chamber is mounted.

Operation of the Mark I injection system:

1) The gas supply valve and the injection valve are closed;
2) The coupling is opened and filled with biomass or plastic;
3) The gas supply valve is opened, filling the loading chamber with inert gas;
4) The feed-valve on the reactor head is opened;
5) The injection pipe-gun is inserted into the reactor chamber;
6) The injection valve is opened; the biomass is forced into the reactor by the inert gas supplied by the hose;

The injection pipe-gun is removed and the feed valve is closed.

Evaluation of Mark I

This system is very inefficient because it requires that the reactor chamber is opened to the atmosphere during the injection process. Large amounts of heated inert gas are dumped into the atmosphere around the reactor and form a big energy loss.

The loading of the injection gun is a tendinous process that takes up a large amount of time. It takes longer to load the pipe-gun than it takes the reactor to pyrolyze the biomass injected by the gun. This dead time is a loss of energy and inert gas.

The diameter of the pipe-gun is very small and thus prevents the use of non-uniform biomass. It can inject small amounts (2-4cm³) of conditioned biomass with circular properties up to a diameter of 2 mm. The biomass that is sticky or very coarse will block the gun.

The biggest problem is the danger of the operation to the operator himself. When the feed-valve of the reactor is opened, very hot gases (+350°C) are pushed out of the reactor in to the surrounding atmosphere. The danger of skin burns is moderate the biggest danger is the inhalation of these hot gases and the danger of the hot gas with char particle for the eyes.

This evaluation indicates that a new system needed to be designed to overcome the efficiency and safety issues.

This resulted in the Mark II design based on the working principle of the pipe-gun but solved the safety issues. A loading chamber with an injection valve for inert gas on de side of the chamber was developed. This chamber is thread mounted on to the feed valve and sealed with a loading valve.

Operation of the Mark II system:

1) The injection valve and the feed valve are closed; the loading valve is open;
2) The chamber is loaded with biomass and the loading valve is closed;
3) The feed valve and the injection valve are opened; the biomass is forced into the reactor by gravity and inert gas pressure;
4) The feed valve and the injection valve are closed.

Evaluation of the Mark II design, after it was tested in the first production test. The design operated perfectly safe, no hot gases escaped from the injection system. The efficiency was questionable, even though the diameter of the injection pipe was larger, the biomass was also less uniform (Pine wood splinters up to 4mm in length, 1mm wide).

This caused the system to block. The biomass fluid quality was so low that it caused obstruction in the loading valve and into the reactor head. The pressure of the inert gas is controlled by the reducer on the gas cylinder and tuned for the main supply of the reactor (0.5 bar or lower). This is pressure is too low to clear the obstructions completely. The obstructed biomass does degrade as it is pyrolyzed, but this takes up too much time to be effective. This system functions perfectly with sand-like biomass.

Also, the entrance from the reactor head into the reactor was obstructed by a smaller diameter opening than the connecting pipe to the feed-valve.

This evaluation inspired the development of the Mark III design.

First, the opening in the reactor head was milled to the same diameter as the pipe that connects the feed-valve to the reactor. This to enlarge the main diameter of the injection system and enabling the use of less uniform biomass.

The Mark III design is no longer based on the injection principle by inert gas. It uses forced piston injection in inerted atmosphere. The loading chamber was adapted, the injection valve now functions as an inert gas valve (1.11) to inert the injection system. A pipe with the loading valve (1.7) was welded under 45° (Y-connection) to the loading chamber. In order to smooth the loading of biomass.

On top of the loading chamber, a custom fabricated connection piece with thread connection was fitted. This enables the mounting of an air pressure powered two-way piston (1.10). The piston physically forces the loaded biomass through the feed valve (1.6) into the reactor. This system was tested during the second productive test and preformed excellent. It operated as expected, all the biomass was injected and no blockage was observed.

The operational procedure can be consulted in the manual located in the addendum

E. <u>The reactor and preheater needed to be isolated by non-flammable insulation;</u>

The preheater and the piping connecting it to the reactor needed non-flammable insulation. The choice was strongly influenced by the cost of the material. Rockwool and Glass wool are two, cheaply available non-flammable insulation materials. Rockwool was chosen because of the negative aspects of Glass wool. When Glass wool comes contact with the skin, its microscopical fibres scratch and cause irritation.

The insulation was applied in blanked form, folded around the components and fixated with iron wire. The insulation blanked was covered with metallic heat resistant foil, double folded aluminium foil (11µm) was used to cover the bare Rockwool surfaces.

F. <u>The preheater was wrongly attached (welded straight) to the frame and bended by thermal stress;</u>

Because the preheater coils are not isolated, a connection between the coils and the frame, creates an earth leak fault. The preheater tube needed to be straightened again to repair this problem. First it was tried with a hydraulic press and pieces of half-pipe to spread the force more equally. This caused deformation (squeezing) of the tube, which is not desired. the other option was thermal quenching of the material to bend the pipe in the opposite direction and straighten it out. Because of the construction material, stainless steel, the material needed to be heated to a high temperature. An acetylene torch was used to heat the pipe and soaked jeans rags to cool it down locally and cause contraction in the steel.

To reinstall the preheater back to the frame, support brackets were crafted to ensure a thermal stress-free support, that allowed expansion and contraction of the preheater.

G. <u>The reactor was very unhandy to move, wheels needed to be installed;</u>

The reactor module has 6 main support struts, under each one a multi directional wheel was installed. Not only make these wheels the module more movable, it also isolates the reactor from the ground. All free components are connected to the main earth connection in the control box by a bonding wire, which in on its turn is connected to the earth pin connection of the power cord.

H. <u>The reactor needed to be tested in trials to determine proper operational procedures;</u>

After repairing the reactor, ensuring safe operation and taking care of the safety issues, tests were conducted to determine proper and safe operational procedures.

I. To reduce the ash content of the final product a cyclone filter in the output flow is needed;

The fluidised bed reactor was developed, to fast pyrolyze plastic's and plastic waste. These products do not form big amounts of char or ash, compared to biomass. To reduce the content of the char and ash in the produced oil, a cyclone filter is placed in series with reactor outlet. To minimize the amount of oil condensation in the cyclone filter, the distance between the reactor outlet and the cyclone filter is kept to the minimum and the filter is wrapped in isolating foil.

The biggest advantage of a cyclone filter is that it is very resistant against clogging. This because of the free flow and particle deposit principle of the filter.

The filter is designed with attention to easy access for cleaning. The ash deposition in the bottom tube of the filter can be removed by removing the bottom screw-cap. The inlet of the cyclone filter is welded tangential on the centrical shape of the filter house. This creates the helical vortex inside the filter which is the basis of its filtering principle. The outlet of the filter is a pipe centred in top of the filter.

The gas flow circles the wall of the filter and banks off to the centre to exit the filter. The larger particles have too much inertia to follow this steep climb and collide with the opposite wall. Once a particle hits the wall, it has lost most of its momentum and settles down in to the bottom part of the filter. The deposited particles can be removed after operation, when the reactor is being cleaned (EMIS, 2015).

The cyclone filter application was tested in the second productive test with pine wood. The pine wood vapours were clean and ash free when captured in the collection bulb. The day after the test run the cyclone filter was opened for inspection. A sticky residue coated the top 2 centimetres of the housing and the outlet riser. Left exposed to open air this became a dry and hard, polish like, layer. On the top of the housing a cyclone shaped deposit, left by the passing gas, was clearly visible. In the bottom collector, small ash particles and tar deposition were observed.

J. An oil recovery system was needed to re-liquefy the gases produced by the reactor;

Once the hot vapours leave the reactor and passed through the cyclone filter they need to be liquefied. Not all gases are condensable and open system is the easiest solution.
The biggest problem is designing a cooling system that is gas sealed and fits on the reactor outlet (copper piping 15mm).

The first attempt existed out of a glass bulb collection vessels (figure 16) with a distillation run off. Over this run off a glass test tube was fitted to have a second gas trap. This construction is fitted over the gas outlet and sealed off with clay. It is cooled with water at ambient temperature. This construction was used during the first two pine wood tests, it proved to be inadequate.

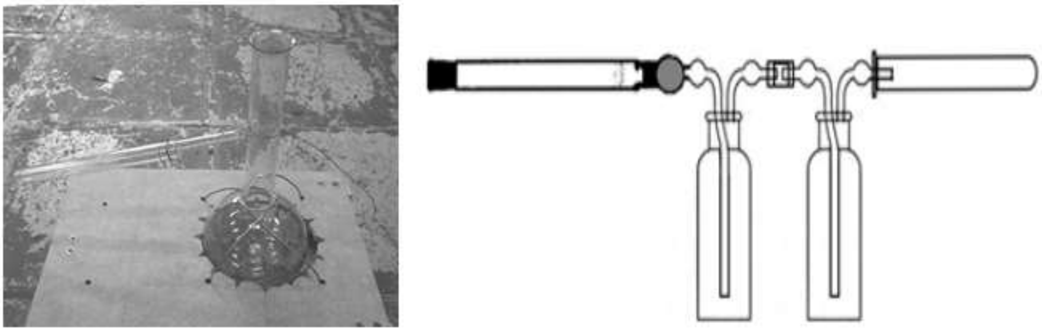


Figure 19. Oil recovery systems.

On the left side, the bulb cooler and on the right, side the gas wash collection system. by Larsen Priem

Two stage gas wash collection system is one of the solutions. (Figure 19)
A conical connection piece in brass, was produced to fit in the sleeve of glass tubing with a conical grinded connection (14 and 14.5mm). Two gas wash bottles in series with top pieces that direct the flow through the bottles would mean a more effective capturing method. A test tube is fitted over the exit and will collect the last fraction. The gas filters were removed of the outlet because the clogging risk by tarry substances in the condensed oil. By lengthening the cooling process and forcing the gas through a longer cooling path, more gases will be condensed. The two stages will provide three different fractions of increasing purity. To increase cooling capacity the installation is cooled with ice, water is added to conduct the heat.

2.2.2 Conditioning of biomass: Practical shredding

An electrical (230V) powered shredder was used, it has a maximum intake wood diameter of 35mm and a capacity of 230kg/h.

The pine wood was already chopped to decimetre long sticks. This was loaded directly into the shredder and shredded in four cycles, after which it was sieved and the bigger particles were shredded again, this process was repeated until the particles met the first stage shredding requirements. The bamboo (*Phyllostachys aurea*) was supplied in + 10 cm diameter stems with a length up to 2 meters. The bamboo was sawed in between the nodes, which we processed separately, and split in to 30cm long, 2cm wide pieces. The nodes were chopped and broken in to smaller pieces. This mix was loaded directly into the shredder and shredded for four cycles, after which it was sieved and the bigger particles were shredded again, this process was repeated until the particles met the first stage shredding requirements.

The second stage shredding was done on a smaller scale with an electrical coffee grinder to condition the biomass to particle size for reactor application. Here a sieving and re-shredding cycle was used to maintain the quality and produce particles, not dust. Both biomass resources were dried in atmospheric conditions for over more than a year.

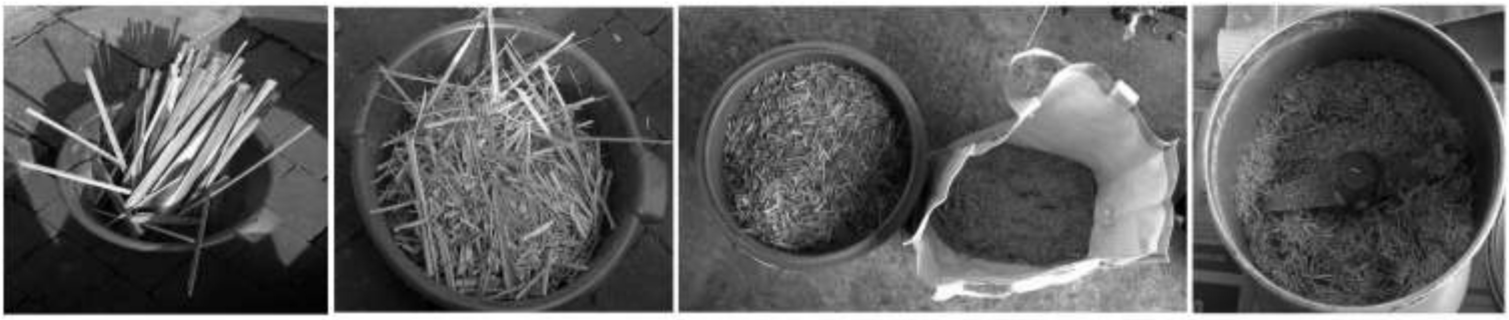


Figure 20. The different shredding stages of bamboo culms to fast pyrolysis feedstock by Larsen Priem

2.3 Pine wood fast pyrolysis tests

We carried out two tests with conditioned pinewood. Test no 1 was made us of the Mark II design injection system. The test was conducted at a reactor temperature of 470°C. The controlled gas flow, between 3-4 m^3/h (50-66l/h) (air setting) with a pressure of around 0.5-1.5 bar(g). The gases were collected with the bulb cooler connected to the reactor outlet and sealed with wet clay. It was cooled in by semi-immersion in a water reservoir at ambient temperature (15°C). A total amount of 50cc of conditioned pine wood was injected. The injection system did not perform optimal and injection was done in different stages. After every injection attempt the biomass blocked the feed valve. During pyrolysis, large amounts of kaki-brown vapours were observed. The bulb cooler tube became coated with viscous droplets and ash particles. The test tube collected around 0.1 ml of brown water like fluid. The water in the cooling reservoir became coated with an oily shine. The test was put to a stop when the cooling water became lukewarm. The cooler system was disabled and the collected samples where left for three weeks in restricted atmospheric conditions at room temperature. The sample in the cooler collected into a dark brown viscous drop. The viscosity increased in the three weeks up to the point is was no longer liquid. The sample in the test tube, which was believed to contain a lot of water decreased to half its volume in three weeks and evaporated completely in one week, being exposed to open air. The evaporation test shows that both fractions contain products that evaporate at atmospheric conditions. Also, this test showed that: a better cooling system needed to be designed and the bad performance of the Mark II injection system led to a mind shift and the development of Mark III. The large amount of ash and particles in the bulb cooler showed the need for a filtration system, a cyclone filter.

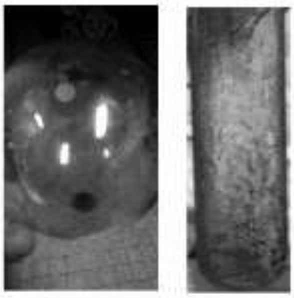


Figure 21. Collected sample of test no. 1.

On the left side, the bulb sample and on the right side, the test tube sample. by Larsen Priem

Test no. 2 was executed with the Mark III injection system; the main objective was to test the working of the Mark III design in operational conditions. The test was conducted at a reactor temperature of 520°C. The gas flow controlled between was between 3-4 m^3/h (50-66l/h) air setting with a pressure of around 0.5-1.5 bar(g). The gases filtrated by a cyclone filter in series with the cooling system the gases were cooled with the bulb cooler connected to the cyclone outlet and sealed with wet clay. The bulb cooler was cooled by semi immersion and water flow cooling from a header tank. A similar amount of conditioned pinewood as in test 1 was injected (50cc). The injection system preformed as expected, only some biomass remained in the angled part of the loading chamber, this can be solved by manually pushing the biomass through the load loading chamber into the injection chamber with a long isolated tool. Like in test no 1: during pyrolysis, large amounts of kaki-brown vapours were observed. The bulb cooler tube became coated with and viscous droplets. Some miniscule spot leaks were detected in the loading chamber weld. The clay sealing between the bulb cooler and the cyclone filter outlet failed at the end of the test resulting in a moderate loss of vapours. The test tube collected around 0.3-0.5 ml of brown water-like fluid. The test was put to a stop when the header tank ran dry. The pine wood vapours were clean and ash-free when captured in the collection jar. The day after the test run the cyclone filter was opened for inspection. A sticky residue coated the top 2 centimetres of the housing and the outlet riser. Left exposed to open air this became a dry and hard, polish like, layer. On the top lid of the housing, a cyclone shaped deposits, left by the passing gas, were clearly visible. In the bottom collector, small ash particles and tar deposition were observed. The test showed that the Mark III injection system works. The cyclone filter preformed excellent by removing many ash particles. On the other hand, the tar like residues deposited in the cyclone filter and formed a hard layer. This kind of deposition can block the system. The cooling system needed improvement to enhance performance, this was implemented by the development of the gas wash cooler/collector.

Tests and evaluation of results of bamboo biomass pyrolysis will be provided separately in an extra addendum chapter.

3 Discussion

3.1 Particle size reduction energy versus energy gain

Here following question arises: Up to what size does the extra energy invested to reduce the particle no longer results in economical and calorically revenue by higher oil quality and quantity, because of its lower residence time and demanded energy input. Determining this size exactly, can only to be done by developing a model to represent the pyrolysis reactor and all the energy it consumes. Once the operational energy balance of the complete plant, all axillary systems, supply chain and biomass production energy cost is known, a practical test can be executed. By testing different sizes and determining the operational yield, it can be compared against the required amount of energy. The exact optimal particle size will defer from biomass type to type and from harvest to harvest.

3.2 When do we stop cooling down?

Depending on the fraction or the amount of liquid product that is desired the cooling level and medium will be selected. The economical and practical aspect demands a fuel that is stable in atmospheric conditions at temperatures between 5 to 30°C. To cool down faster and more effectively, a lower temperature is required. When we use fast pyrolysis to create resources other than fuel, this decision will be based up on the desired product and the processing requirements. To completely capture the whole output of the reactor is almost impossible. The cooling down to liquefy gases like methane (-163°C) is in this case not economically beneficial. A better way is to use these gases as direct fuel for the reactor heating.

3.3 What energy do we use to create fuel?

To produce a completely renewable and sustainable energy source, all the energy used to create it, must also be renewable. In the first place, we can use the side products of the pyrolysis oil production to fuel the process. The non-condensed gases can be burned to generate heat and electricity in a gas turbine application. The char can be burned directly to generate heat or to raise steam from a boiler. We can also use other renewable energy sources like: solar, wind, hydro-electric and tidal power to supply the reactor plant.

3.4 Slow diesel engines: optimal use of FPO?

Even though medium speed engines can be adapted to run on HFO grade fuel, two stroke engines do it at the highest efficiency. They are robust and large, which makes them suited for adaptions and allows easy installation of auxiliary equipment. Dual fuel engines already exist and it is a matter of adapting the injection and fuel system to FPO combustion. The extra equipment necessary is not particularly large. Slower rpm and longer combustion allow slower and multistage combustion. Techniques like this can be used to optimally in slow two stroke engines to completely control the FPO behaviour during combustion and control emissions. Today the high investment costs and low oil prices hinder and forestall the development of practical tests.

3.5 Acids in FPO: a biting problem

FPO has a very high acidity (pH 2 – 3) compared to HFO. Using this oil in a conventional engine will have disastrous effects on tanks, lines and equipment. Adaption of the engine to resist the high acidity will be a challenge for the manufactures. By using acid resistant materials like stainless steel of high quality and using acid resistant gasket material, we have excluded the problem. Bunker tanks will need coatings or must be constructed out of stainless steel.

4 Conclusion

Bamboo is an energy crop that shows huge potential as biomass fuel source. The high renewal rate and the possibility of world-wide application as a crop with a comparable energy content as that of broad-leaved trees is promising, however pyrolysis oil is not suited as a diesel fuel additive. Because of the polar composition of the FPO it is practically not miscible with any petroleum based fuel. As reported in the chapter ‘Mixing FPO with diesel’ it is partially miscible in bio-diesel. It is better to conclude that FPO should be used as a homogenous fuel source and should not be mixed with petroleum fuels. FPO burns only at very high pressures and temperatures which are not achieved in the compression stroke of operational diesel engines. The first solution is the addition of cetane enhancers like bio alcohols and methanol, to initiate combustion. This combined with combustion air preheating, makes it possible to operate medium to high speed four stroke diesel engines on FPO. The use of pilot injection with more volatile fuel, combined with staged FPO injection in dual fuel common rail systems for medium and slow speed engines are theoretically better alternatives. Two stroke engines are considered an excellent choice as FPO consumer, no practical trials have been reported yet, the high investment costs and low oil prices hinder and forestall the development of practical tests. The weight/energy balance of FPO fuels is almost half of that of diesel, the energy/volume balance is almost 70% of diesel. Even though this is a big disadvantage to HFO, FPO might a very favourable bunker fuel for ships wanting to meet SECA restrictions without installing scrubbers and breaking heads over scrubber-sludge discharge. The advantage of FPO over de-sulphured HFO is that there is that: no additional sulphur is generated during the production. The conversion of FPO to transportation fuel is only mildly positive, when taking in consideration the addition of catalytic fines and high energy costs.

The production of the AMA fast pyrolysis (fluidised bed) reactor must be further optimised to obtain bigger yields. A possible option is the conversion to a continuous feed system and installing a char removal system in the reactor bed. A partial gas-recirculation system is also an option to reduce energy consumption and boost production of lower density fuels at the cost of total FPO yields. Improvement and further development of a multistage cooler will also increase FPO yields. For practical engine tests a big investment in a dual fuel test engine is required. Tests with boiler burners should be easier. The current small production capacity of the reactor only allows small scale analysis.

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6 Addendum

6.1 AMA fast pyrolysis (fluidised bed) reactor operation manual

This manual is originated from the desire to have a solid basis of standard procedures for operating of the fluidized bed fast pyrolysis reactor. It was obtained by studying the operational plant, including adaptions. As the plant is further developed, the manual should be updated as well. Deviating from safe operational procedures can have severe consequences because of the high risks involved. This manual aims to reduce these risks to an acceptable minimum.

Content:

1. Safe operation and dangers
2. Simple controller operation
3. Reactor layout and parts
4. Operation of the reactor:
    I. **Pre-operation checks**
    II. **Start up and operation**
    III. **Shut down and cleaning**
    IV. **Post operation checks**
5. Indication lights and their meaning

1. Safe operation and dangers

For the safe operation of the fast pyrolysis reactor module, it is important to understand the risks involved in its operation. By following the recommendations, the risks can be reduced to a minimum. The pyrolysis reactor operates at very high temperatures (+350°C) and is constructed almost completely out of metal parts. Due to conductivity, the metal surfaces of the reactor will become hot. Even the foil covered insulation can become dangerously hot. Never open or remove any valves, lids or parts, that are part of the hot gas flow circuit or open the circuit to the atmosphere during operation.

Fire

The preheater of the reactor is not controlled and operates at 100% capacity once activated by the switch on the control box. Never operate the preheater longer than 3 minutes continuously with minimum intervals to let it cool down. Never leave the reactor unattended when the preheater is activated and monitor the reactor temperature closely.

The main heating of the reactor temperature is controlled, however not use the reactor for periods longer than 1 hour continuously, foresee sufficient interval to let the reactor cool down again. Not only to minimalize fire danger but to prevent thermal deformation of the reactor module and its piping. When finished, store the reactor free-standing in a dry, ventilated space.

Asphyxiation

The reactor’s propelling gas flow is inert gas; the non-condensable gases are dumped into the atmosphere after cooling. The pyrolysis reaction of the reactor, depending on the product injected, can produce asphyxiating gases.

Never operate the reactor in an enclosed space or a space with restricted ventilation. It is advised that the reactor is operated outdoors during dry and windy weather.

Toxicity

The pyrolysis reaction of the reactor, depending on the product injected, can produce toxic gases and vapours. When severe irritational or harmful products are produced by the reactor, shut down the reactor immediately. Do not drink, swallow or ingest substances produced by the reactor. Never operate the reactor in an enclosed space or a space with restricted ventilation. It is advised that the reactor is operated outdoors during dry and windy weather. Try to avoid inhalation of the gases and vapours escaping from the reactor. Do not drink, swallow or ingest substances produced by the reactor. In case of swallowing or ingestion, contact a doctor or call +32 (0)70 245 245 for the poison center in Belgium.

Electrocution

The reactor and the frame are connected to the earth, through the PE pin of the socked. The installation mainframe is connected with bonding wires to the main earth connection in the control box. Without the bonding wires, the installation is completely isolated from the earth because the physical separation by rubber wheels. If the insulation of the reactor is breached and the coils touch the frame, the leak current switch of the electrical installation supplying the reactor will switch off. The reactor has no own electrical protection.

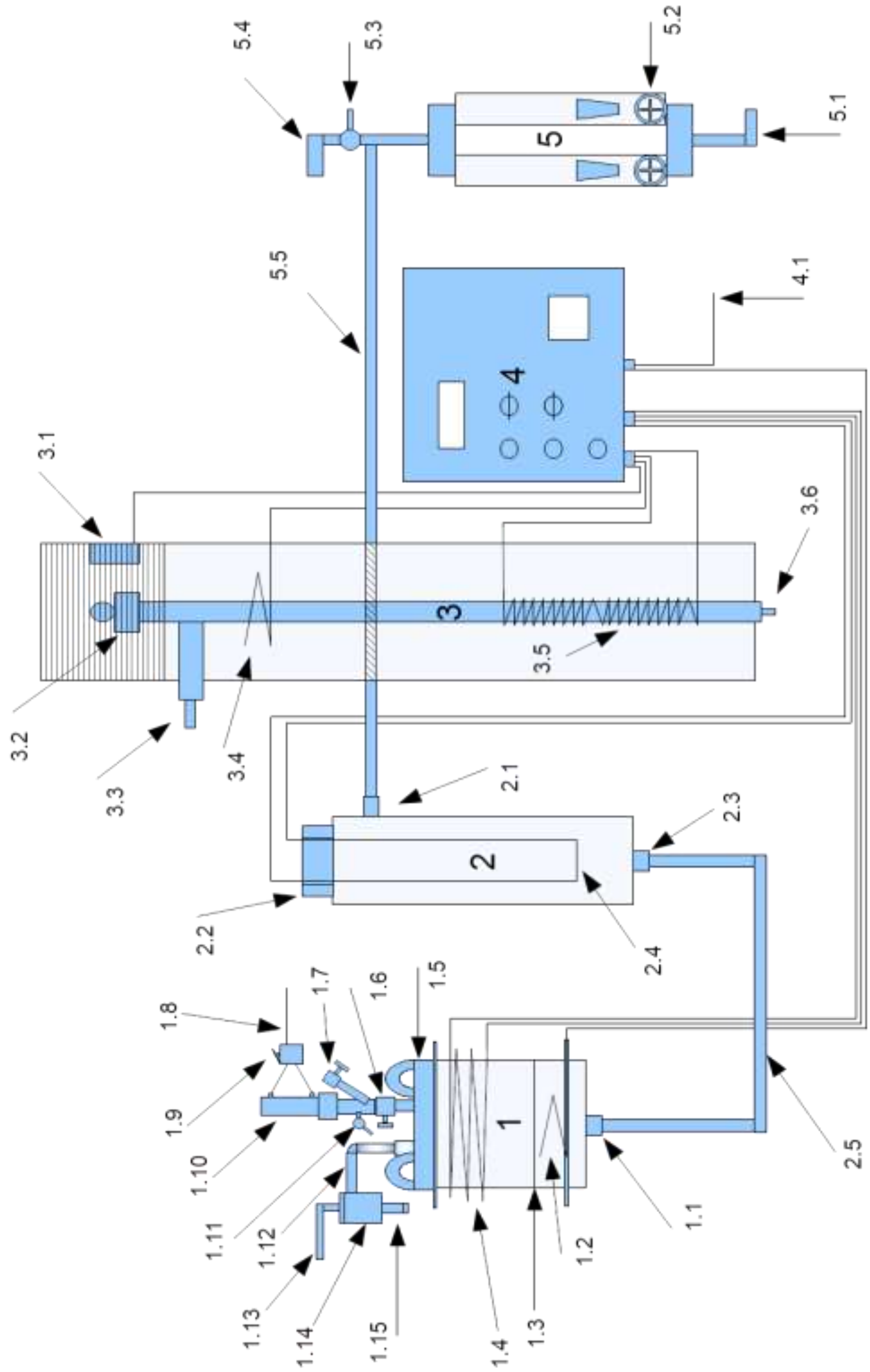
PPE

Wear fitting heat resistant clothing like, coveralls approved for welding. Do not operate the reactor without wearing heat resistant gloves like, welding approved gloves. Protect your eyes with approved safety goggles.

2. Simple controller operation

The proportional controller boots automatically when the reactor module is supplied with power. The controller has a simple lay out and is easily adjusted with two buttons.
The actual temperature is displayed in red next to the PV (Present Value) indication. The set point temperature is displayed in green next to the SV (Set Value). The set point can be lowered or raised by operating the buttons with the double arrow upwards (raise) or the double arrow downwards (lower).

3. Reactor layout and parts



Reactor Parts

1 Fluidised bed reactor
1.1 Gas supply connection (inlet)
1.2 Temperature sensor
1.3 catalytic fluid bed
1.4 Electrical heating coils
1.5 Reactor head
1.6 Feed valve
1.7 Load valve
1.8 service air connection
1.9 3/2 injection control valve
1.10 Injection piston
1.11 Inert gas valve
1.12 Reactor exhaust pipe (outlet)
1.13 Cyclone filter outlet to cooler
1.14 Cyclone filter housing
1.15 Filter deposit
2 Preheater
2.1 Inert gas supply connection preheater (inlet)
2.2 Preheater head
2.3 Preheater outlet connection
2.5 Connection pipe Reactor- Preheater
3 Tube reactor
3.1 Ventilator
3.2 Reactor screw lid
3.3 Reactor exhaust connection
3.4 Temperature sensor
3.5 Electrical heating coils
3.6 Inert gas supply connection (inlet)
4 Control box
4.1 Power supply cord
5 Float gauge meters with flow control
5.1 Main inert gas supply connection (inlet)
5.2 Flow control valves
5.3 Small diameter inert gas supply valve
5.4 Small diameter inert gas connection
5.5 Main inert gas supply pipe

4. Operation of the reactor:

I Pre-operation checks

Before start following initial checks should be made:

- Make sure the pressure of the propellant gas is sufficient for the length of the operation and the connection to the float meters with flow control is in place and tightened.
- Make sure the flow control valves (5.2) on the float meters (5) are closed.
- Open the main valve on top of the gas cylinder partially. Check the reducer and calibrate on 0.5 bar(g) minimum and check for leaks.
- Open the flow control valves (5.2) and register flow through the system, this to ensure that the piping (1.12, 2.5, 5.5) and the cyclone filter (1.13) are free of blockage. Also, check for leaks in the system.
  Close the flow control valves again.
- Insure power is available and the alarm indication is off: once the cord (4.1) is plugged in, the controller will start up and display the actual temperature in the reactor.
- Check the service air supply (1.8), operate the injection piston (1.10) and discern free movement.
- Switch both switches on the control box (4) from 0 to 1 and back to 0 to observe the working of the indicator lights.
- Check that connection and sealing between the output of the reactor and the gas cooling-collector are in place.
- Close the feed and load valve (1.7, 1.6) of the injection system.
- Program the desired reactor temperature in to the controller.

If any irregularities are detected the operation should be shut down immediately. Operation can only be reinitiated if the cause is detected and the module is restored to correct operational capability.

II Start up and operation

1. Open the load valve (1.7) and load the injection system with biomass, leave the load valve slightly open.
2. Inert the injection system:
   - A. Open the small diameter inert gas supply valve (5.4)
   - B. Open the inert gas (1.11) valve on the injection system;
   - C. Close the load valve (1.7);
   - D. Close the inert gas valve (1.11).
3. Switch on the main heating.
4. Wait till the temperature inside the reactor reaches the desired level. Then, open slightly the flow control valve (5.2) to the required flow rate. Check that there is no gas leaking from any connections.
5. Start the preheater and wait for 30 seconds.
6. Open the feed valve (1.6) on the reactor.
7. Use the injection control valve (1.9) to operate the piston twice.
8. Close the feed valve (1.6)
9. Switch off the preheater 30 seconds after the injection
10. Return to step 1

The char from the reactor is normally carried away by the inert gas and captured by the cyclone filter, however during operation char deposition in the reactor will start to build up. There is no way to remove the Char from the reactor during operation, the reactor needs to be shut down and cleaned out. The amount of Char deposition stands in direct relation with the amount of biomass injected in the reactor. Monitoring the injected amount enables the maximum length of an operation. When large amounts of char start to build up in the reactor, layers of 2 to 5 mm, the pyrolysis reaction is no longer homogeneous and the fluidised bed loses its function.

III Shut down and cleaning

1. Shut off the nitrogen supply by closing the flow control valve (5.2) and the main valve on the cylinder. Disconnect the nitrogen supply to the float meters (5.1). Close the flow control valves (5.2).
2. Switch off the main heating, do not unplug the power yet.
3. Wait till the reactor has cooled down completely, and is cool enough to be touched. Due to the insulation, this can take some time. You can monitor the reactor temperature on the controller.
4. You can already shut off the service air (1.8) and disconnect the tube.
5. Once cooled down, unplug the power (4.1).
6. Detach the oil recovery system from the cyclone filter outlet (1.13)
7. Detach the cyclone filter (1.14) from the reactor outlet.
8. Clean the cyclone filter:
    I. Open the bottom lid (1.15) of the cyclone filter and remove the deposition;
    II. Remove the top of the cyclone filter (use spanner size 10);
    III. Clean the filter chamber;
    IV. Reassemble the filter in reversed order.

9. Disconnect the nitrogen supply to the inert gas valve (1.11) of the injection system.
10. Dismantle the injection system in following order:
    A. Detach the inert gas valve (1.11) and the reactor outlet pipe (1.12) using a spanner (size 22 and 24);
    B. Remove the injection chamber with the injection piston (1.10) still attached, leave the feed valve (1.6) on the reactor head (1.5);
    C. Unscrew loading valve (1.17) (If it’s stuck, use a pipe wrench or a large adjustable spanner);
11. Unscrew the reactor head (1.5).
12. Remove the char from the reactor bed (1).
13. Clean the reactor head (1.5), loading chamber and temperature sensor (1.2)
14. Reassemble the reactor and the injection system in reversed order.
15. Attach the cyclone filter (1.14) to the reactor outlet (1.13).

16. Coil the tubes and power cord (4.1) around the control box (4).
17. Store the reactor free-standing in a dry, ventilated space.

IV Post Operation checks

- Check the condition of the power cables (1.4, 2.4) leading to the reactor (1) and preheater (2) for signs of melting, singe or carbonisation. Check the sensor cables as well. (1.2)
- Check the pressure in the nitrogen cylinder and makes sure the main valve on the cylinder is firmly closed.
- Check that all switches on the control box (4) are in the 0 position
- Check and makes sure that the air supply (compressor) is switched off.

5. Indication lights and their meaning:

When operating the designated switches for both heating circuits at start up and their respective indication lights remain dark, do as follows.
When the preheater light fails, listen carefully for the ‘clack’ sound of the power relay that controls the preheater when you switch from 0 to 1 and back to 0. If you hear the sound, the preheater circuit is working accordingly. Check the light bulb and its connections.

If you are not certain or are unable to detect the relay from switching, open the control box by detaching the front panel. Now check again the operation of the relay by switching 0 to 1 and back to 0. A circuit fault of loose connection can be repaired easily; broken or malfunctioning components need to be replaced.

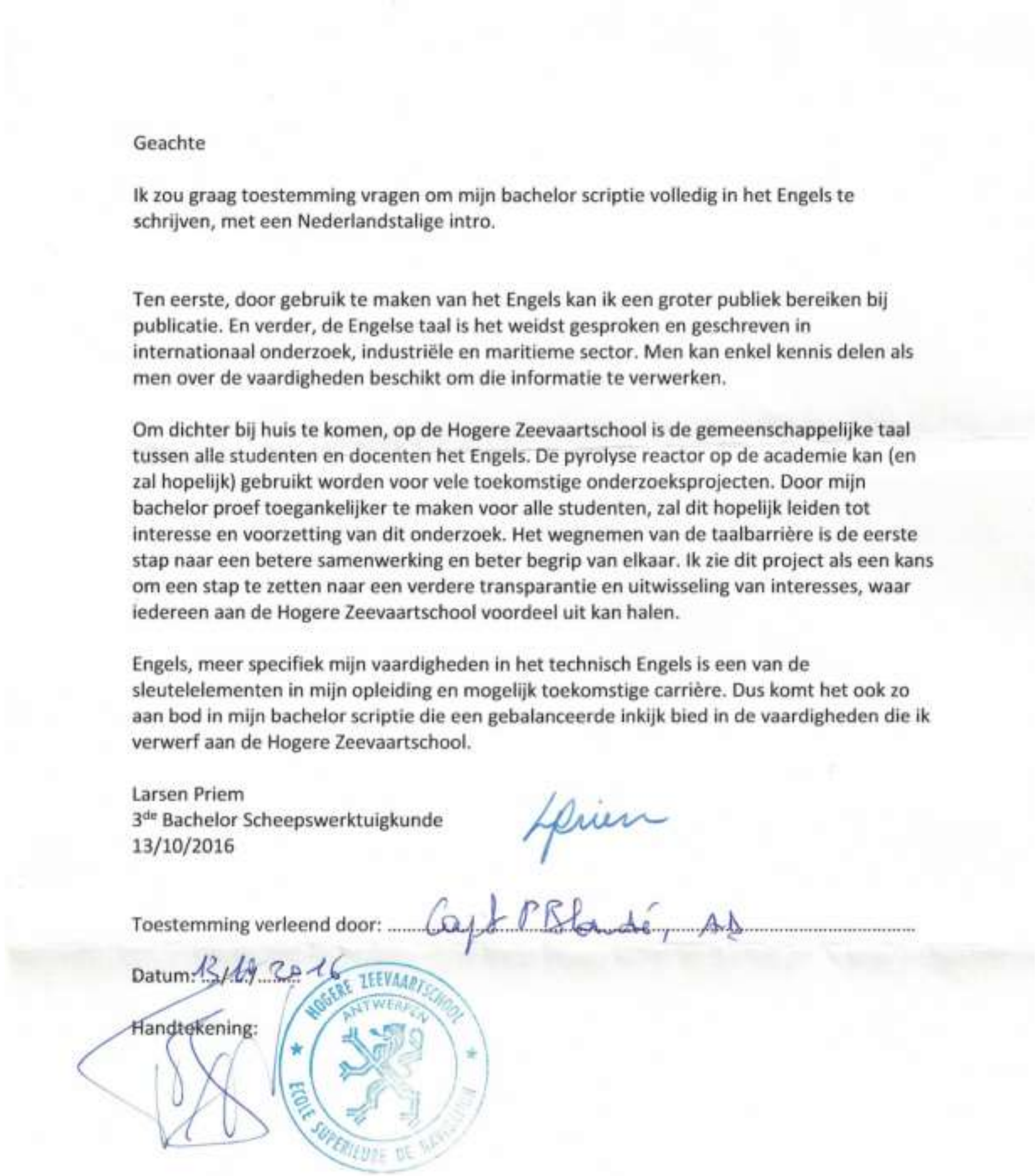
When the main light fails to operate, open the control box by detaching the front panel. The electronic relay controlling the power to the main heating is equipped with a green indication led and a red alarm led. When the green led is functioning, the circuit is working accordingly, check the light bulb and its connections. A circuit fault of loose connection can be repaired easily; broken or malfunctioning components need to be replaced.

The red led can indicate overheating or an internal fault, check the component's manual or contact the manufacturer.
When replacing a lightbulb install the correct one:

- Preheater and Alarm indicator light 230V bulb;
- Main heating indicator light 24V bulb.

Alarm indication light
Do not start reactor operation when this indicator light is lit.
- When the alarm light is lit during the start-up check, this indicates the following: The Omron relay is unable to switch or does not receive power, but the system receives power. This can be caused by a circuit fault or a loose connection. These faults are easily repaired; broken or malfunctioning components need to be replaced.
- When the alarm light becomes lit during operation
Switch off the main and or preheating, stop the operation of the reactor and stop the gas flow. This indication means that Omron relay failed or no longer receives power but the main system is still receiving power. This can be caused by a circuit fault or a loose connection. These faults are easily repaired; broken or malfunctioning components need to be replaced.

6.2 Permission English thesis



Geachte

Ik zou graag toestemming vragen om mijn bachelor scriptie volledig in het Engels te schrijven, met een Nederlandstalige intro.

Ten eerste, door gebruik te maken van het Engels kan ik een groter publiek bereiken bij publicatie. En verder, de Engelse taal is het weidst gesproken en geschreven in internationaal onderzoek, industriële en maritieme sector. Men kan enkel kennis delen als men over de vaardigheden beschikt om die informatie te verwerken.

Om dichter bij huis te komen, op de Hogere Zeevaartschool is de gemeenschappelijke taal tussen alle studenten en docenten het Engels. De pyrolyse reactor op de academie kan (en zal hopelijk) gebruikt worden voor vele toekomstige onderzoeksprojecten. Door mijn bachelor proef toegankelijker te maken voor alle studenten, zal dit hopelijk leiden tot interesse en voorzetting van dit onderzoek. Het wegnemen van de taalbarrière is de eerste stap naar een betere samenwerking en beter begrip van elkaar. Ik zie dit project als een kans om een stap te zetten naar een verdere transparantie en uitwisseling van interesses, waar iedereen aan de Hogere Zeevaartschool voordeel uit kan halen.

Engels, meer specifiek mijn vaardigheden in het technisch Engels is een van de sleutelelementen in mijn opleiding en mogelijk toekomstige carrière. Dus komt het ook zo aan bod in mijn bachelor scriptie die een gebalanceerde inkijk bied in de vaardigheden die ik verwerf aan de Hogere Zeevaartschool.

Larsen Priem
3de Bachelor Scheepswerktuigkunde
13/10/2016
LPriem

Toestemming verleend door: Capt P Blondé, AD

Datum: 13/11/2016

Handtekening:

HOGERE ZEEVAARTSCHOOL ANTWERPEN

FACULTEIT SCHEEPSWERKTUIGKUNDE

A Report on the FPO Production test with Bamboo

Addendum to: An approach to fast pyrolysis-oils as diesel fuel additive

Larsen Priem

Promotor: Dr. Geert Potters

Academiejaar: 2016- 2017

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FPO Production test with Bamboo

To evaluate the applied pyrolysis characteristics of bamboo and the behaviour of the Antwerp Maritime Academy's pyrolysis reactor in batch production, we conducted a practical experiment.

Figure 1 Reactor configuration

by Larsen Priem

I. Parameters

The experiment was carried out with following parameters:

Reactor temperature: 450°C

Propellant gas: Nitrogen

Gas flow: 50l/min at 1 bar(g)

Feedstock: *Phyllostachys aurea*

Dimensions of the feedstock: 4mm long with a 2mm diameter (maximum) splinters

Processed amount: 94 grams

Cooling system: 2 gas wash bottles (250ml) in series with return tube and connection piece

Sealing medium: Exhaust sealing paste

Cooling medium: water with ice to enhance conduction

II. Phase 1

The experiment was carried out over a time span of four hours with two breaks of one hour to let the reactor cool down. The operation was carried out as dictated in the *AMA fast pyrolysis (fluidised bed) reactor operation manual*. The proper welding approved PPE's were worn.
In the first stage of the test the amount of material to be injection was determined, several times the injector chamber became clogged because of overfilling. This was overcome by slowly trickling the shredded bamboo, +-10grams at a time into the reactor injection chamber. Stirring the biomass loosely with a long isolated tool prevented blockage.

Figure 2 Cooling and recovery system

By Larsen Priem

The main part of the bamboo was pyrolyzed in mere second resulting in burst of heavy and dark yellow vapours being released by the reactor. After the second injection, droplets began to form in the connection tube. The negative inclination of the tube to the first wash bottle caused droplet collection in the connection tube. At the same time droplet deposition in the return tube was detected as well.

Figure 3 Collection of droplets in the connection tube

by Larsen Priem

The amount of vapours produced after the seventh injection was much lower than after previous injections. Around the same time oil droplets became visible in the wash bottles. Blockage of the cyclone filter or exhaust tube was suspected. The reactor was shut down and dismantled for inspection. When removing the cyclone, exhaust tube the collected liquid was saved. The tube end was cracked during the removal of the exhaust paste.

Figure 4 Char collection in the reactor chamber (left) and exhaust tube clogging (right) by Larsen Priem

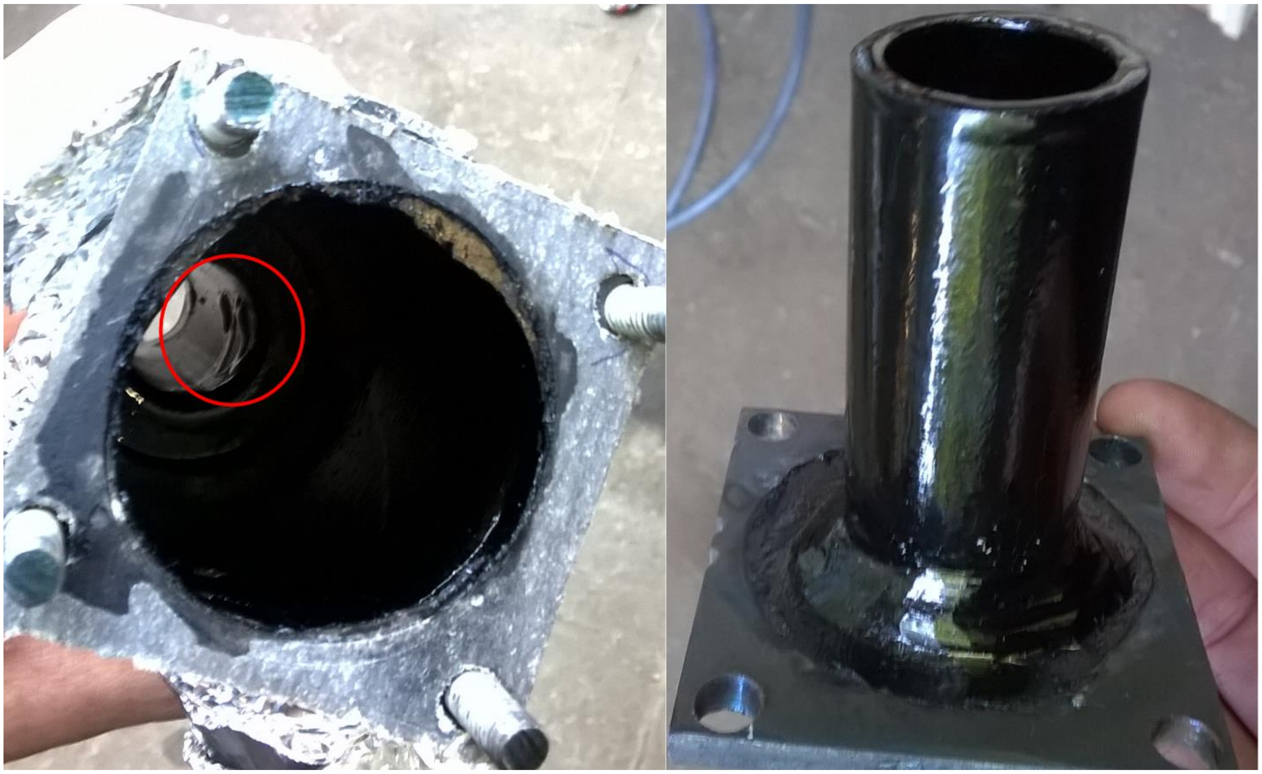
Deposition of char and tar fractions clogged the reactor exhaust to the cyclone filter. The low flow rate of the propellant gas reduced the amount of char carried over to the cyclone filter. The reactor exhaust pipe and chamber were cleaned and the char was collected.

During this intermediate evaluation moment, we saw some parameters and settings that needed improvement. Because of the negative inclination, the reactor was raised in the second part of the test. The connection tube was not replaced because it complicated the oil collection. The flow rate was not adapted, increased flow and respective char carriage would result in faster clogging, batch removal of char was opted as the easiest solution.

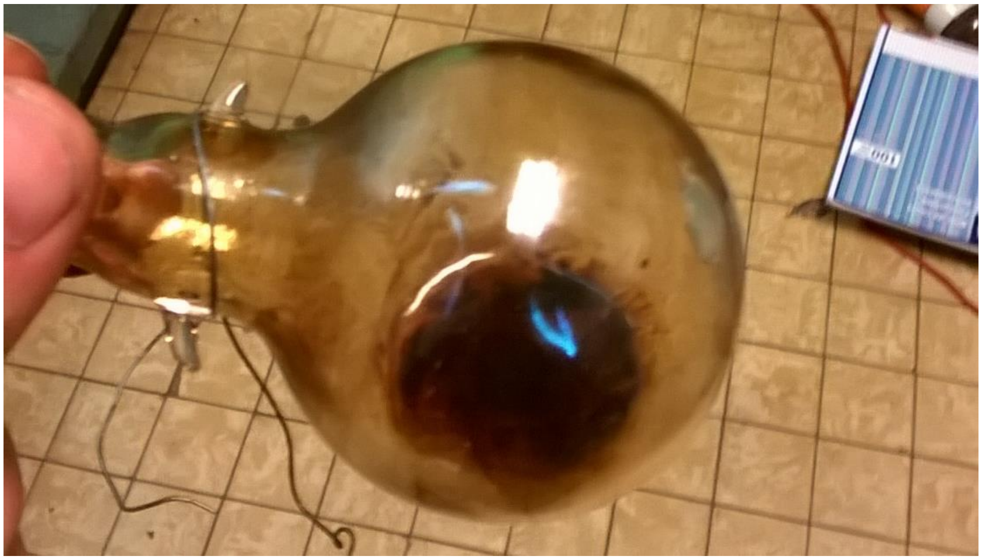
III. Phase 2

During the second part of the test small leaks from the reactor head were observed, the sealing between the head and the housing was partly compromised. The amount of oil amassing in the gas wash bottles increased only slightly. The production was put to a stop when the amount of vapours decreased again and a smiliar amount of injections (6) was was reached.

The reactor was shut down and dismantled for inspection and cleaning. The char was collected and the blockage in the reactor exhaust pipe was removed. The removal of the connection tube and the inclination correction, resulted in fewer oil collection in the cyclone exhaust tube.



In the bottom collection lid of the cylone filter a sticky tar residue was discoverd. The filter houding contained mor tar droplets, they were highly viscous and solidfied when cooled down to ambient temperatures. The tar droplets were partly collected. The housing was coated with a hard layer of tar resin.



IV. Results

A total amount of 1.5cc oil was recovered, a fraction of the first gas wash bottle was lost during disassembly of the cooling system. The oil recovered decreased in viscosity in proportion with the increasing stage of cooling. The oil was collected in one sample bottle and sealed. The oil had a temperature of +3°C.

V. Conclusion

The test was representative and showed the operational conditions of fast pyrolysis of bamboo. Several fractions were recovered: oil, tar, char. The production capacity is very low but equivalent to the reactor size and dimensions. The cooling system preformed as required but can be further improved. Extra insulation or heating between the cooling system and the exhaust should be considered. A positive inclination between the reactor and the cooling system is a necessity for complete oil recovery. Evolving to a singular collection point is most desirable. But cooling must be controlled because of the high viscosity of the oil at low temperatures. To decrease tar deposition in the cyclone filter, heating should be considered. This will also increase the amount of collected oil, but the oil viscosity will be higher. The clogging of the reactor exhaust by char can only be solved by a char removal system or the production must be limited to small batch operation with intermediate cleaning. In the current configuration, the reactor is only suitable for production of small batch test samples.