Bio-oil in stationary gas turbines

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Technical & economical feasibility

Responsibility

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Index

Appendices

Figures

Tables

1 Introduction

Ingenia, Heat Power and TU/e were granted a contribution from the NEO (New Energy Research) programme executed by SenterNovem to perform a broad investigation on the feasibility of the use of biofuels, especially bio-oils, in gas turbines.

1.1 Background

Interest in biofuels for energy generation is increasing for several reasons:

- To reduce CO_2 emissions (in line with the Kyoto protocol);
- To reduce dependency on fossil fuels like natural gas and fossil oil (natural gas prices have been rising strongly in recent years and deficits in supplies are forecasted);
- Guaranteed renewable electricity feed in tariffs and /or obligations;
- Fossil fuel taxes;
- Because of the local availability of suitable side streams like biogas and vegetable or animal oils and/or fats.

However, application of biofuels in gas turbines has not turned to practice yet. This has a severe impact on the amount of sustainable CHP (combined heat and power), as many modern CHP applications are based on gas turbines. Furthermore, the number of new to be erected gas turbine CHP installations increases further worldwide and the pressure on the natural gas market will increase accordingly. At the moment of writing the small and intermediate scale gas turbines that this investigation focuses on, supply some 30% of the Dutch electricity market.

At one side, the overwhelming majority of gas turbines in running on natural gas only (without dual fuel burners) and operators of gas turbine CHP's are reluctant to change. Owners who were considering a conversion have prematurely put this conversion on hold. The main reason mentioned for this is unfamiliarity with and uncertainty about the short and long term effects of biofuels on the operation of the turbines. Even incidental practical tests with biofuels have only lasted shortly and have been cancelled prematurely.

On the other side, some gas turbine manufacturers indicate that the application of biofuels in (new) oil burners should be possible, but any guarantee considering up-time and efficiency of the gas turbine is withdrawn immediately in case of conversion or even short term tests with biofuels. Guarantees and

the claims connected to this regarding up-time and efficiency of the turbine, are the most critical point in this market. The main reason indicated by turbine manufacturers is that biofuel specifications are unknown to them.
As a third reason biofuels suppliers have insufficient knowledge of the specific fuel requirements for gas turbines to be able to contribute to the development of specifications.
It can be said that the turbine owners, turbine manufacturers and the biofuel suppliers lack the necessary references to develop guarantees c.q. fuel specifications.

Furthermore, biofuels need extensive refining (filtering, dewatering, degumming, …) in order to ensure compliance with stringent quality specifications. Also, the storage (i.e. corrosion by free fatty acids in vegetable oils) and shelf life (e.g. oxidation stability) of biofuels are a point of attention. To the preparation and storage of biofuel also technical-economical risks are connected, that are insufficiently known, as a result of which biofuels are not practically applied in turbines.

1.2 History of gas turbines and their fuels

Of the various means of producing mechanical power the turbine is in many respects the most satisfactory. The absence of reciprocating and rubbing members means that balancing problems are few, that the lubricating oil consumption is exceptionally low, and that reliability can be high.
Serious development of the gas turbine began not long before the Second World War with shaft power in mind, but attention was soon transferred to the turbojet engine for aircraft propulsion. The gas turbine began to compete successfully in other fields only in the mid nineteen fifties, but since then it has made a progressively greater impact in an increasing variety of applications. [Cohen-Rogers]

1.3 Gas turbine technology

1.3.1 Conventional technology, land-based and aeroderivative

Conventional gas turbines systems comprise simple cycle gas turbines, heat exchanger gas turbines and combined steam- and gas turbine systems (combined cycles).

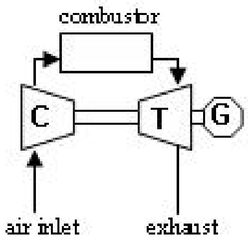


Figure 1-1 Simple cycle gas turbine

The simple cycle gas turbine (fig 1-1) can be roughly divided into land-based and aeroderivative gas turbines. Land based gas turbines typically have a pressure ratio of 7 up to 15, while aeroderivatives typically have a pressure ratio of 15 up to 40. On average the aeroderivative gas turbines have a higher efficiency and specific power than land-based gas turbines, but they are also more complex and less rigid.

The efficiency of a gas turbine can be elevated by implementing a heat exchanger to recuperate the energy of the exhaust gases, this is usually referred to as the recuperative cycle (fig 1-2)

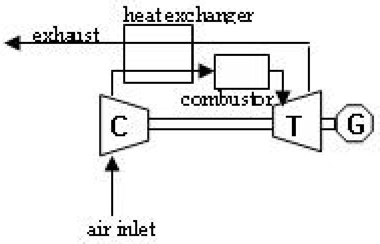


Figure 1-2 Recuperative gas turbine

Another way of raising the efficiency is implementing the gas turbine in a combined cycle. The two main conventional types of combined cycle are shown in figure 1 and 2. Figure 1 shows the multi-shaft combined cycle and figure 2 shows the single-shaft combined cycle. Both make use of a gas turbine consisting of a compressor (C), combustion chamber, and turbine (T). The steam cycle consists of a steam generator (waste-heat boiler), steam turbine (ST), condenser, water pump and generators. Both combined cycles are shown driving generators, because that is their main application.

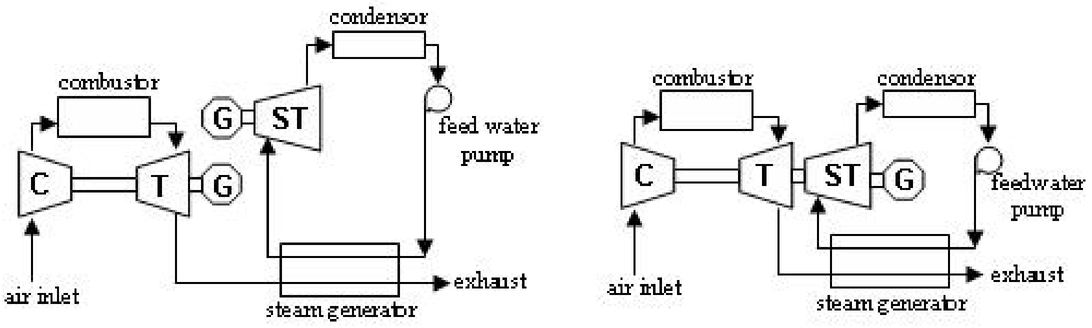


Figure 1-3 The multi shaft combined cycle (l) and the single shaft combined cycle (r)

1.3.2 Rankine Compression Gas turbine (RCG)

The RCG is a new type of combined steam and gas turbine installation (combined cycle). Current combined cycle installations take a relatively long time to start and can barely operate on (rapidly) changing speeds, let alone give torque to the load when it is standing still. Because of these load characteristics combined cycle installations are very successfully employed in base-load power generation, but not in mechanical drives and maritime propulsion. The innovation involves a combined steam and gas turbine installation that returns all shaft power by means of one free power turbine (figure 1-4). This means that this combined cycle installation is going to be able to operate at rapidly changing speeds, and give torque when the load is standing still. For a combined cycle, this is unique. With this new technology, it is going to be possible to employ combined cycle installations in applications, where they could not have been employed before: mechanical drives and maritime propulsion. Also, the RCG will offer very high flexibility in combined heat and power (CHP) applications. The invention is called Rankine Compression Gas turbine (RCG).

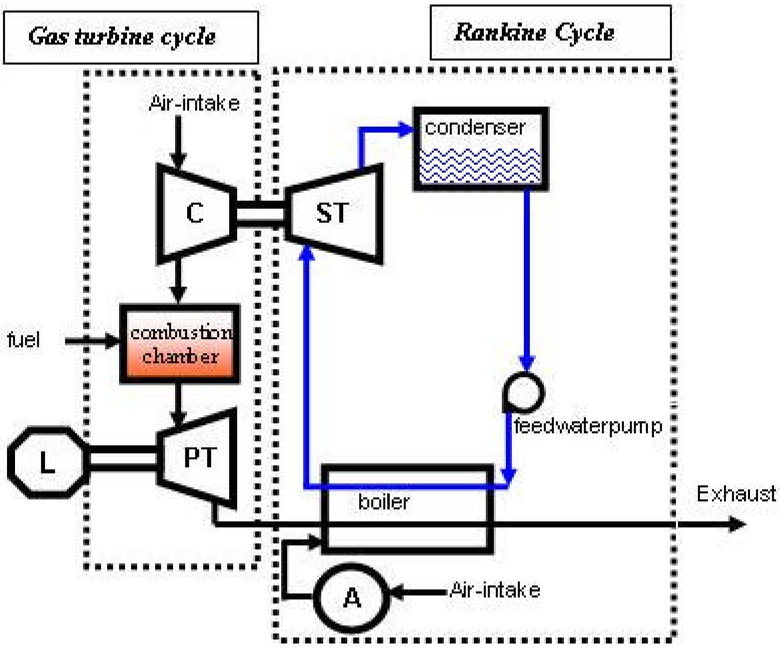


Figure 1-4 Schematic of the Rankine Compression Gas turbine

1.3.3 Comparison of the Simple Cycle, Recuperative cycle, conventional Combined Cycle and the RCG

For power generation both gas turbines and internal combustion engines are employed. Both have their own merits and disadvantages and to choose between the internal combustion engine and the gas turbine, many considerations have to be taken into account. However, this paper is restricted to the research of the application of bio-fuels in gas turbines, therefore only gas turbine based layouts are compared and considered.

Figure 1-5 shows the results regarding the obtainable thermal efficiency of the Simple Cycle, recuperative cycle and the RCG at varying Turbine Inlet Temperature (TIT). The efficiency shown at a certain TIT is the efficiency of a certain installation with a turbine with that TIT as its maximum.

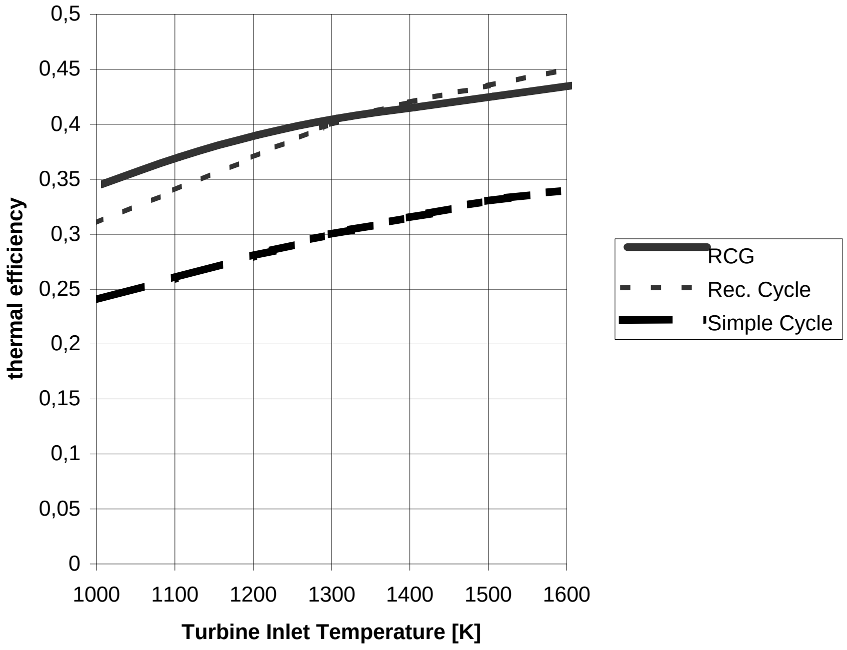


Figure 1-5 Thermal efficiency of the RCG, recuperative cycle and simple cycle at varying TIT

These efficiencies were calculated assuming design choices that are realistic and typical for the shaft power range of 1-10MW. Figure 1-5 shows that the efficiencies of the Simple cycle are much lower than of the recuperative cycle and the RCG, which of course was to be expected. The results show that both the RCG and the Recuperative cycle can obtain efficiencies of about 30% up to about 45% in a range of realistic TIT’s. At the current maximum Turbine Entry Temperature for an uncooled turbine, 1300 K, they both rate a thermal efficiency of about 40%. At TIT’s higher than 1300 K the recuperative cycle has somewhat higher efficiencies than the RCG, but at TIT’s below 1300 K it is the RCG that has the highest efficiencies. It must be noted that the differences between the RCG and the recuperative cycle are small, and that the assumptions made are a little bit in favour of the recuperative cycle. These efficiencies were calculated, assuming modest component efficiencies, and without intercooling. Figure 1-6 shows the corresponding pressure ratios of the compressor in the gas turbine cycle for the RCG, Recuperative cycle and Simple cycle.

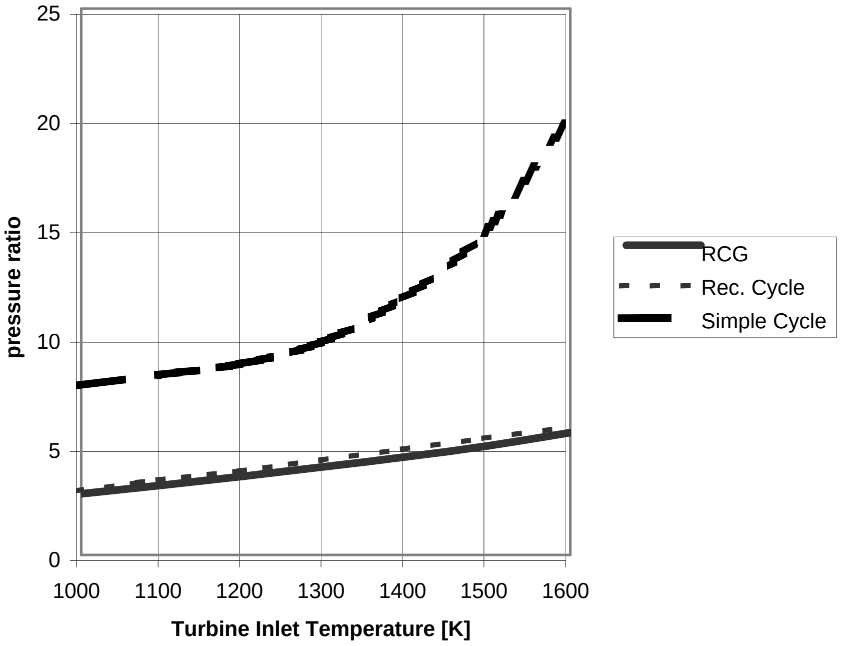


Figure 1-6 Pressure ratio of the RCG, recuperative cycle and simple cycle at varying TIT

It can be seen that the pressure ratios of the simple cycle are much higher than those of the RCG and the recuperative cycle. This follows from the earlier discussed assumption to compare the simple cycle at pressure ratios with a good balance between thermal efficiency and specific power, because it is not possible to optimize for maximum thermal efficiency; for the simple cycle at maximum thermal efficiency, the specific power is equal to zero. The pressure ratio of the recuperative cycle is optimized for maximum thermal efficiency, and the pressure ratio of the RCG follows from the balance between the power of the steam turbine and the power consumption of the compressor.

Most striking is that the equilibrium pressure ratios of the RCG and the pressure ratios at optimum efficiency for the recuperative cycle are of the same magnitude. Furthermore, these pressure ratios can be realized with a centrifugal compressor. So the efficiencies of the RCG shown in figure 1-5, are those of a very robust RCG-installation: centrifugal compressor in the gas turbine cycle, impulse steam turbine and low-pressure boiler in the steam cycle.

So it can be concluded that the RCG will be an appealing alternative next to the recuperative cycle, when a higher efficiency than that of the simple cycle is preferred. Of course existing combined cycles can achieve efficiencies of up to 54%. One could conclude that therefore it is no use introducing the RCG. That would be a false conclusion: the RCG is not meant to be a competitor of the existing combined cycles. The purpose of the RCG is, to make it possible to employ a combined cycle installation in the range where they could not be employed until now; the small and mid-power range. This is the power range that is appealing for decentralized CHP bio-fuel installations. Currently, conventional combined cycles are not available in this power range because they lack the operational flexibility and rigidness that is demanded in this segment.

2 Fuel characteristics

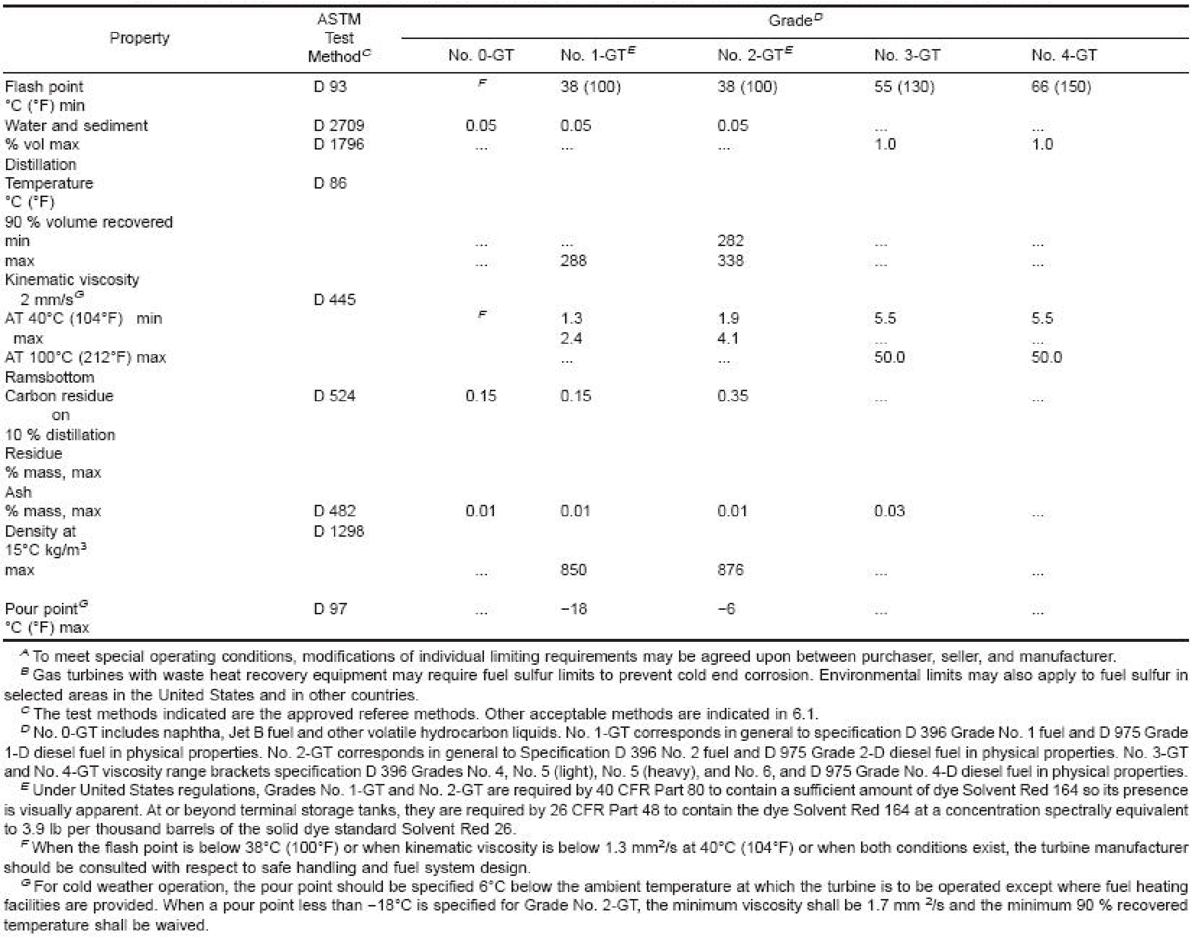
Gas turbines are characterised by pressurised combustion (ca. 14-30 bar) and consequent expansion of the flue gases in a turbine. A large advantage of a gas turbine compared to a piston engine like a diesel engine, is that a continuous flame is present. A direct disadvantage is the sensitivity of the high temperature turbine section's blades for corrosion and fouling. Hence most gas turbines have more strict fuel requirements (0,01% - 0,03% ash etc.). The most common fuels for gas turbines nowadays are liquid petroleum distillates and natural gas. The main focus in this report will be on the properties of fossil oils and bio-oils.

2.1 Fossil oils

2.1.1 Stationary gas turbine fuels

In the table below the ASTM 2880 standard for liquid fossil fuels in gas turbines has been included. The fuels No. 0-GT, No. 1-GT and No. 2-GT (naphtha – diesel) are common for gas turbines. Typically these fuels are a bit heavier (up to 850/876 kg/m^3) than the kerosenes (up to 750/845 kg/m^3) discussed in the next paragraph. As they don't need to resist the extremely low temperatures high in the atmosphere, like aviation fuels have to, their pour point limit is less stringent.

Table 2-1 ASTM Standard D2880 – Fuel oils for gas turbines



Property	ASTM Test Method[C]	Grade[D]				
		No. 0-GT	No. 1-GT[E]	No. 2-GT[E]	No. 3-GT	No. 4-GT
Flash point	D 93	[F]	38 (100)	38 (100)	55 (130)	66 (150)
°C (°F) min						
Water and sediment	D 2709	0.05	0.05	0.05	...	...
% vol max	D 1796	...	...	...	1.0	1.0
Distillation						
Temperature	D 86					
°C (°F)						
90 % volume recovered						
min		...	...	282	...	...
max		...	288	338	...	...
Kinematic viscosity						
2 mm/s[G]	D 445					
AT 40°C (104°F) min		[F]	1.3	1.9	5.5	5.5
max			2.4	4.1	...	...
AT 100°C (212°F) max			...	...	50.0	50.0
Ramsbottom						
Carbon residue	D 524	0.15	0.15	0.35	...	...
on						
10 % distillation						
Residue						
% mass, max						
Ash						
% mass, max	D 482	0.01	0.01	0.01	0.03	...
Density at	D 1298					
15°C kg/m³						
max		...	850	876	...	...
Pour point[G]	D 97	...	−18	−6	...	...
°C (°F) max						

[A] To meet special operating conditions, modifications of individual limiting requirements may be agreed upon between purchaser, seller, and manufacturer.

[B] Gas turbines with waste heat recovery equipment may require fuel sulfur limits to prevent cold end corrosion. Environmental limits may also apply to fuel sulfur in selected areas in the United States and in other countries.

[C] The test methods indicated are the approved referee methods. Other acceptable methods are indicated in 6.1.

[D] No. 0-GT includes naphtha, Jet B fuel and other volatile hydrocarbon liquids. No. 1-GT corresponds in general to specification D 396 Grade No. 1 fuel and D 975 Grade 1-D diesel fuel in physical properties. No. 2-GT corresponds in general to Specification D 396 No. 2 fuel and D 975 Grade 2-D diesel fuel in physical properties. No. 3-GT and No. 4-GT viscosity range brackets specification D 396 Grades No. 4, No. 5 (light), No. 5 (heavy), and No. 6, and D 975 Grade No. 4-D diesel fuel in physical properties.

[E] Under United States regulations, Grades No. 1-GT and No. 2-GT are required by 40 CFR Part 80 to contain a sufficient amount of dye Solvent Red 164 so its presence is visually apparent. At or beyond terminal storage tanks, they are required by 26 CFR Part 48 to contain the dye Solvent Red 164 at a concentration spectrally equivalent to 3.9 lb per thousand barrels of the solid dye standard Solvent Red 26.

[F] When the flash point is below 38°C (100°F) or when kinematic viscosity is below 1.3 mm²/s at 40°C (104°F) or when both conditions exist, the turbine manufacturer should be consulted with respect to safe handling and fuel system design.

[G] For cold weather operation, the pour point should be specified 6°C below the ambient temperature at which the turbine is to be operated except where fuel heating facilities are provided. When a pour point less than −18°C is specified for Grade No. 2-GT, the minimum viscosity shall be 1.7 mm ²/s and the minimum 90 % recovered temperature shall be waived.

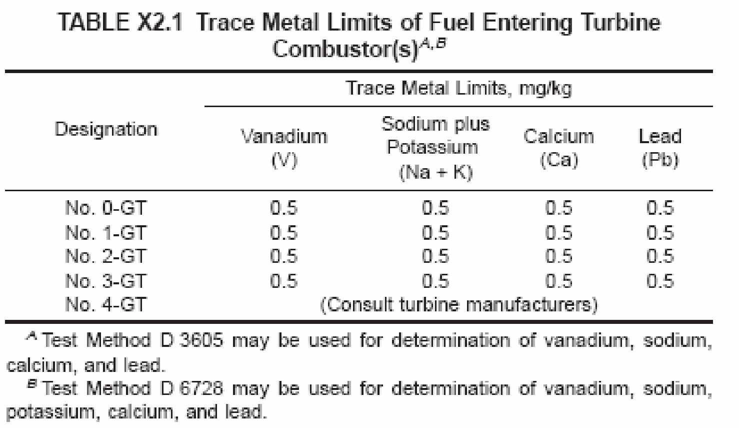


TABLE X2.1 Trace Metal Limits of Fuel Entering Turbine Combustor(s)[A,B]

Designation	Trace Metal Limits, mg/kg			
	Vanadium (V)	Sodium plus Potassium (Na + K)	Calcium (Ca)	Lead (Pb)
No. 0-GT	0.5	0.5	0.5	0.5
No. 1-GT	0.5	0.5	0.5	0.5
No. 2-GT	0.5	0.5	0.5	0.5
No. 3-GT	0.5	0.5	0.5	0.5
No. 4-GT	(Consult turbine manufacturers)			

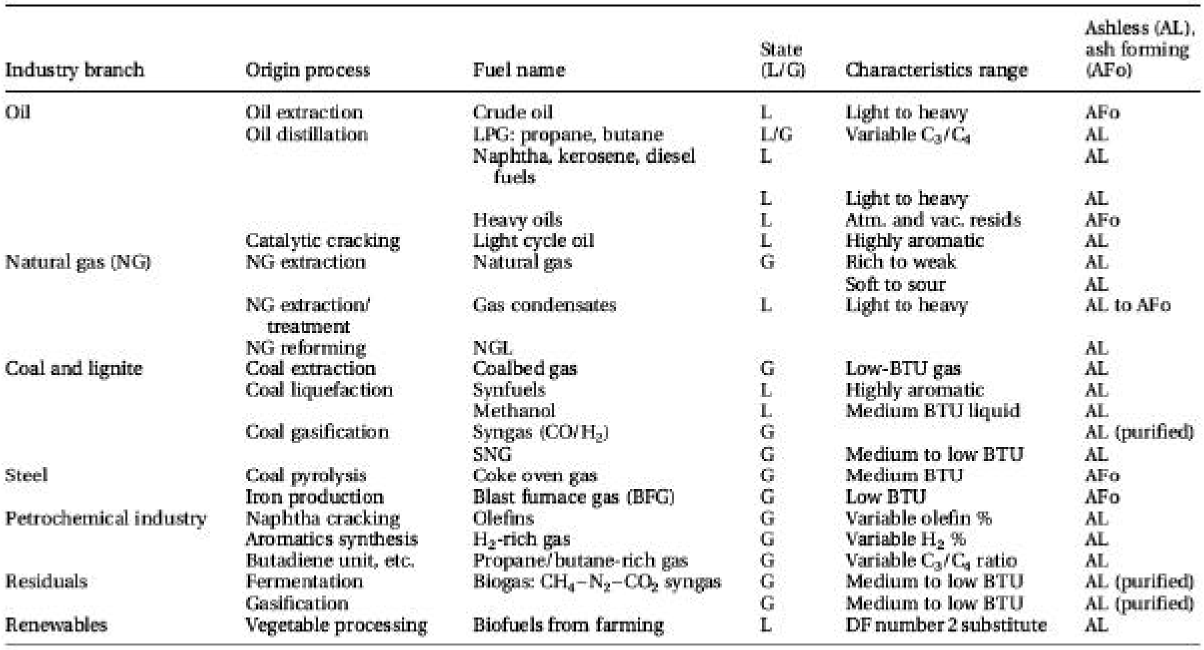
[A] Test Method D 3605 may be used for determination of vanadium, sodium, calcium, and lead.

[B] Test Method D 6728 may be used for determination of vanadium, sodium, potassium, calcium, and lead.

2.1.2 Other fossil fuels

Often a difference is made between ash forming fuel oils (for instance: Heavy Fuel Oil, HFO; Crude Oil; Residual Fuel Oils; No. 6 Fuel, Bunker C) and ashless fuels (e.g. Petroleum Distillate Oil; No. 2 distillate fuel oil; Kerosene, Naphtha; Diesel fuel oil). The table below gives a comprehensive overview of many fuels that are suitable for gas turbines, in which the difference between ashless and ash forming is clearly indicated.

Table 2-2 Classification of most important gas turbine fuels [IMechE 2005]



Industry branch	Origin process	Fuel name	State (L/G)	Characteristics range	Ashless (AL), ash forming (AFo)
Oil	Oil extraction	Crude oil	L	Light to heavy	AFo
	Oil distillation	LPG: propane, butane	L/G	Variable C_3/C_4	AL
		Naphtha, kerosene, diesel fuels	L		AL
			L	Light to heavy	AL
		Heavy oils	L	Atm. and vac. resids	AFo
	Catalytic cracking	Light cycle oil	L	Highly aromatic	AL
Natural gas (NG)	NG extraction	Natural gas	G	Rich to weak	AL
				Soft to sour	AL
	NG extraction/ treatment	Gas condensates	L	Light to heavy	AL to AFo
	NG reforming	NGL			AL
Coal and lignite	Coal extraction	Coalbed gas	G	Low-BTU gas	AL
	Coal liquefaction	Synfuels	L	Highly aromatic	AL
		Methanol	L	Medium BTU liquid	AL
	Coal gasification	Syngas (CO/H_2)	G		AL (purified)
		SNG	G	Medium to low BTU	AL
Steel	Coal pyrolysis	Coke oven gas	G	Medium BTU	AFo
	Iron production	Blast furnace gas (BFG)	G	Low BTU	AFo
Petrochemical industry	Naphtha cracking	Olefins	G	Variable olefin %	AL
	Aromatics synthesis	H_2-rich gas	G	Variable H_2 %	AL
	Butadiene unit, etc.	Propane/butane-rich gas	G	Variable C_3/C_4 ratio	AL
Residuals	Fermentation	Biogas: $CH_4-N_2-CO_2$ syngas	G	Medium to low BTU	AL (purified)
	Gasification		G	Medium to low BTU	AL (purified)
Renewables	Vegetable processing	Biofuels from farming	L	DF number 2 substitute	AL

Worldwide there seem to be some gas turbines that run on heavier kinds of heavy distillate or residual fuel oil (comparable to No. 5 heating oil conform ASTM D 396) in Florida (FPC, Debary PS), Saudi Arabia (SCEC, Ryad, Frame 7's crude oil), Iraq (Quds, crude oil, GE Frame 9's), China, Spain, Indonesia and Morocco. These installations are heavy industrial gas turbines that are not of lighter aeroderivative design.

Especially the Siemens (AlfaLaval) SGT 500 seems to be very suitable to use HFO (IF180 standard, <180 Cst @ 50°C, 5% CCR, 0,1% ash, <75% aromatics, 4,5% Sulphur) while also the Hitachi H25 and H15, the Alstom GT13 (with only one pot-type burner) and the GE Frame 7 and Frame 9 machines seem to be suited for HFO or even light crude oil. There is always some kind of pre-treatment (centrifuging and/or washing) involved as will be shown in section 3.1.

Apart from heavy heating oil, a range of products from conventional refining of fossil oil is potentially suitable as a fuel in gas turbines. The diagram below gives an overview of the refining process and products. The well known kerosene fractions can be recognized at the right hand side as middle distillates. All products that are theoretically suited as a gas turbine fuel, are marked in a grey box.

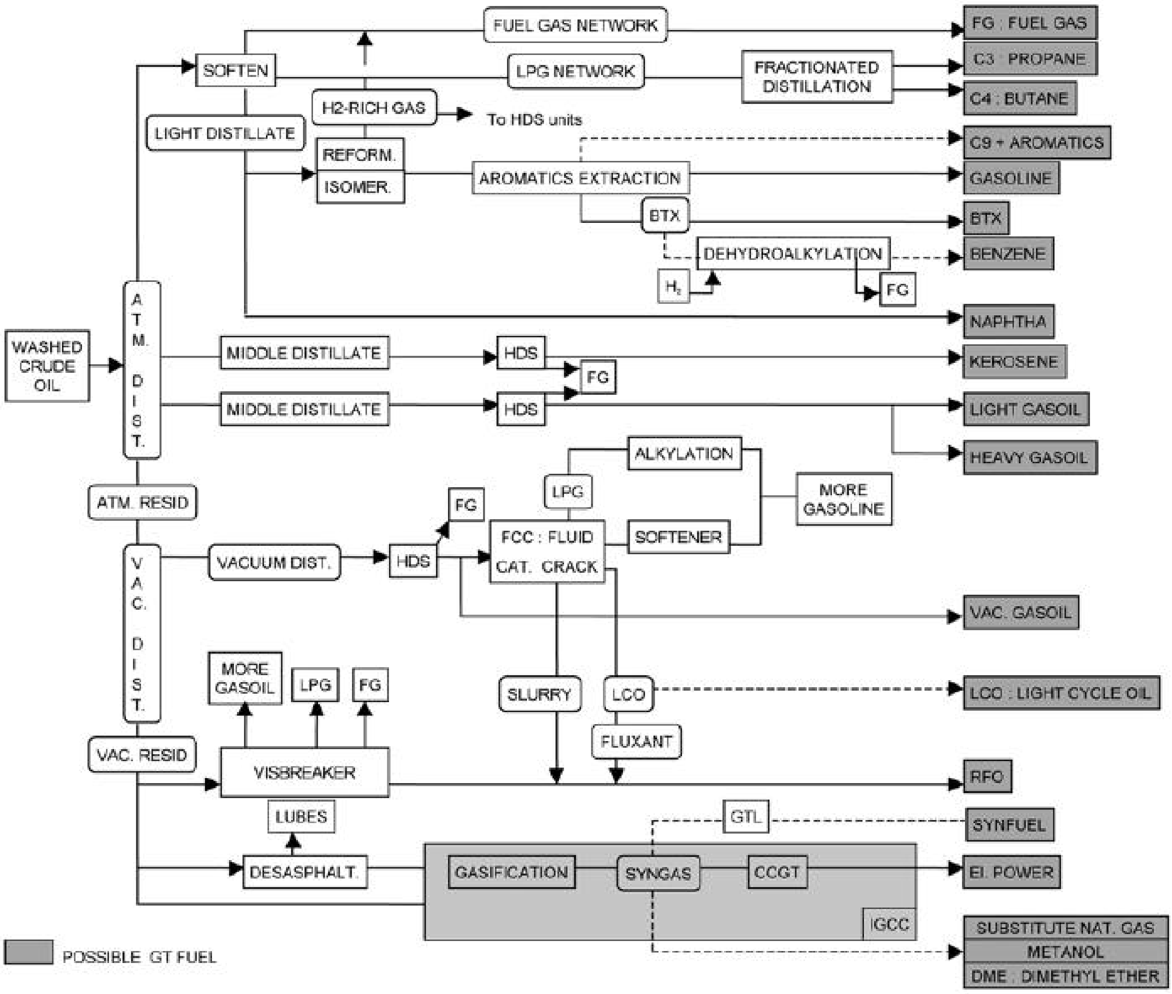


Figure 2-1 Modern refining diagram for fossil oil [IMechE 2005]

2.2 Bio-oils

2.2.1 General introduction to fats and oils

Animal and vegetable fats are mixtures of triglycerides, that means esters from glycerin (1,2,3-propanetriol) and three fatty acid chains. Fatty acids with a length of 14, 16 and 18 carbon atoms are mostly found. Fatty acids and glycerin are the ‘building blocks’ of fats and oils (see figure).

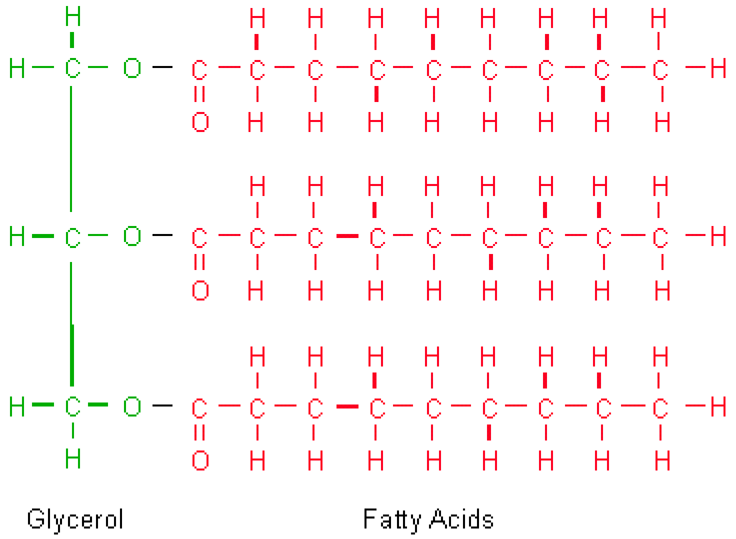


Figure 2-2 General structure of a fat (oil)

A fatty acid consists of a chain of carbon atoms with a methyl group at one side and a carboxylic acid group on the other side. Hydrogen atoms are connected to the carbon atoms, their number is dependent on the fatty acid being saturated or unsaturated (see figure).

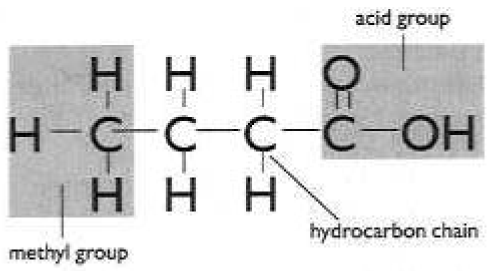


Figure 2-3 A fatty acid

When a fatty acid contains as many hydrogen atoms as it can hold, it is called ‘saturated’. If hydrogen atoms are missing and these are substituted by a double bond between the carbon atoms the fat is called ‘unsaturated’. A mono-unsaturated fatty acid contains one double bond; multiple double bonds make a multi-unsaturated acid. In these multiple unsaturated fatty acids the hydrogen atoms may be ordered in two ways, being the cis- and trans-configuration.

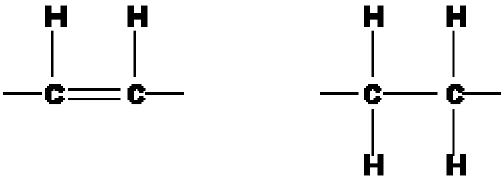


Figure 2-4 Unsaturated/saturated bond in fatty acid (detail)

In the figure above an unsaturated fatty acid in cis-configuration and its saturated counterpart are displayed. “Cis” means that the hydrogen atoms adjoining the double bond are located at the same side (in this case the upper side). The cis-configuration occurs naturally. The double bond’s position determines the fatty acid’s name. The names omega 3 and omega 6, for instance, mean fatty acids where the double bond is located at the third and the sixth carbon atom, respectively. Every type of fatty acid contains a carboxylic acid group that makes the connection to the glycerin.

The extent to which a fat is saturated influences the physical properties of the fat. The more saturated, the more solid it is at room temperature. A liquid (and hence, unsaturated) fat is also referred to as ‘oil’. In nutrition saturated fats are usually regarded as having adverse health effects. Vegetable fats are a source of unsaturated fatty acids. The figure below shows a distribution of the saturated, mono-unsaturated and multiple unsaturated fatty acids in vegetable oils.

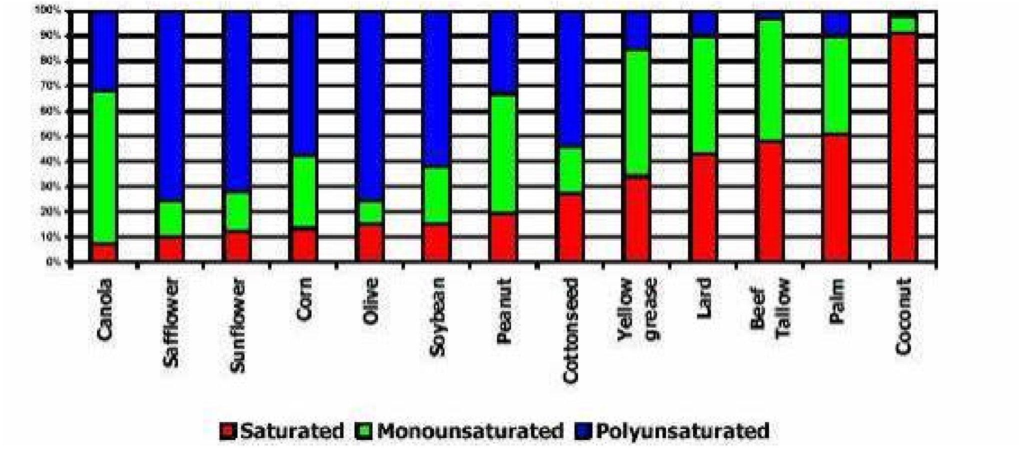
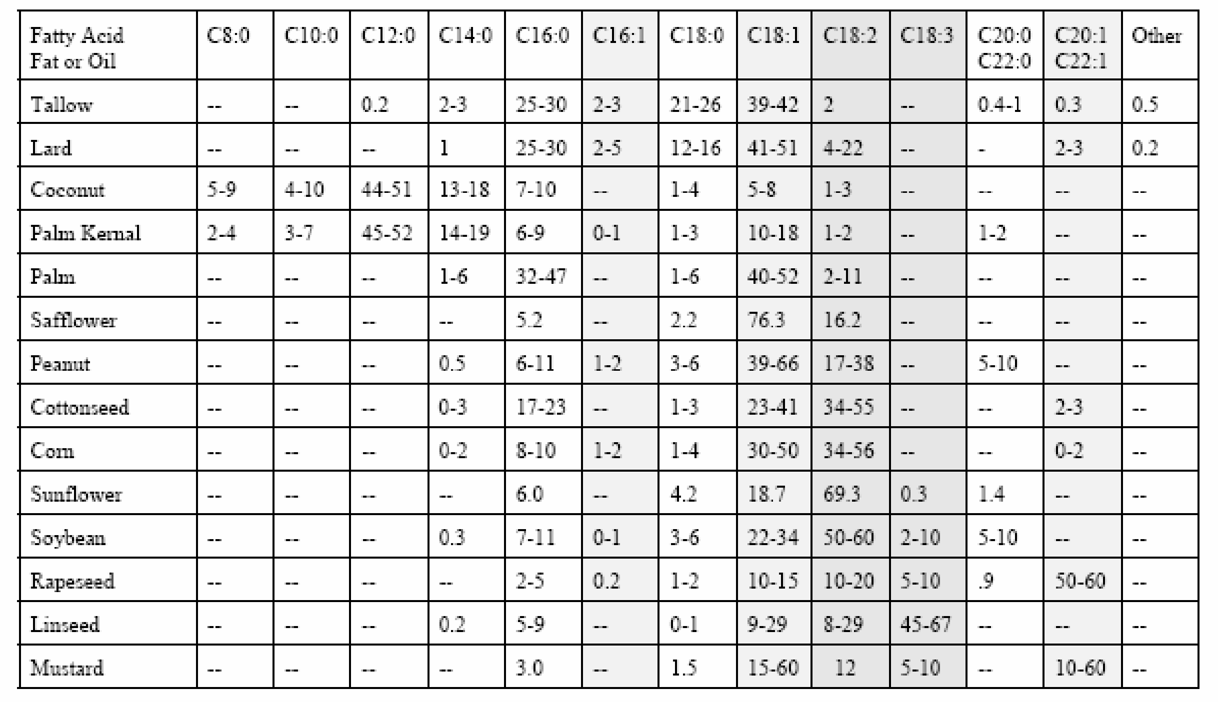


Figure 2-5 Distribution of saturated and unsaturated fatty acids in vegetable oils

All fats contain both saturated and unsaturated fatty acids, but the nomenclature depends on the kind that is predominant. Most vegetable oils are called unsaturated because they contain in majority mono- and multi unsaturated fatty acids. A rule of thumb can be that saturated fats are solid at room temperature and mostly originating from animal sources. Nearly all unsaturated fats are liquid at room temperature and are of vegetable origin. These vegetable fats can be hardened by hydrogenation: in this process hydrogen atoms are added to the double bonds in the unsaturated fatty acid chains, hence saturating the chains. A disadvantage in nutrition technology is that in this process also trans-fatty acids can be formed that have adverse health effects. Hydrogenated oils are used in food preparation like margarine production. The process is performed by leading hydrogen through the fat. It makes the fat more thermally stable and increases the processing ability and shelf life, because more unsaturated bonds in the fat cause more instability and hence processing difficulties.

Table 2-3 shows the composition of several vegetable oils.



Fatty Acid Fat or Oil	C8:0	C10:0	C12:0	C14:0	C16:0	C16:1	C18:0	C18:1	C18:2	C18:3	C20:0 C22:0	C20:1 C22:1	Other
Tallow	--	--	0.2	2-3	25-30	2-3	21-26	39-42	2	--	0.4-1	0.3	0.5
Lard	--	--	--	1	25-30	2-5	12-16	41-51	4-22	--	-	2-3	0.2
Coconut	5-9	4-10	44-51	13-18	7-10	--	1-4	5-8	1-3	--	--	--	--
Palm Kernal	2-4	3-7	45-52	14-19	6-9	0-1	1-3	10-18	1-2	--	1-2	--	--
Palm	--	--	--	1-6	32-47	--	1-6	40-52	2-11	--	--	--	--
Safflower	--	--	--	--	5.2	--	2.2	76.3	16.2	--	--	--	--
Peanut	--	--	--	0.5	6-11	1-2	3-6	39-66	17-38	--	5-10	--	--
Cottonseed	--	--	--	0-3	17-23	--	1-3	23-41	34-55	--	--	2-3	--
Corn	--	--	--	0-2	8-10	1-2	1-4	30-50	34-56	--	--	0-2	--
Sunflower	--	--	--	--	6.0	--	4.2	18.7	69.3	0.3	1.4	--	--
Soybean	--	--	--	0.3	7-11	0-1	3-6	22-34	50-60	2-10	5-10	--	--
Rapeseed	--	--	--	--	2-5	0.2	1-2	10-15	10-20	5-10	.9	50-60	--
Linseed	--	--	--	0.2	5-9	--	0-1	9-29	8-29	45-67	--	--	--
Mustard	--	--	--	--	3.0	--	1.5	15-60	12	5-10	--	10-60	--

Table 2-3 The fatty acid composition of different vegetable oils

2.2.2 Properties of oils and fats for fuel

The properties of any fuel are to meet certain standards, else bad engine performance, severe damage and/or excessive emissions may be the result. Vegetable oils are no exception to this. In Germany a wide-spread research project was performed to determine quality standards for vegetable oil as a fuel. The research was performed by the ‘Bayerische Landesanstalt für Landtechnik’ and was supported by the Bavarian government and numerous companies. The result of this project was a quality standard for vegetable oil as a fuel, called the ‘Weihenstephan’ standard or RK 2000.

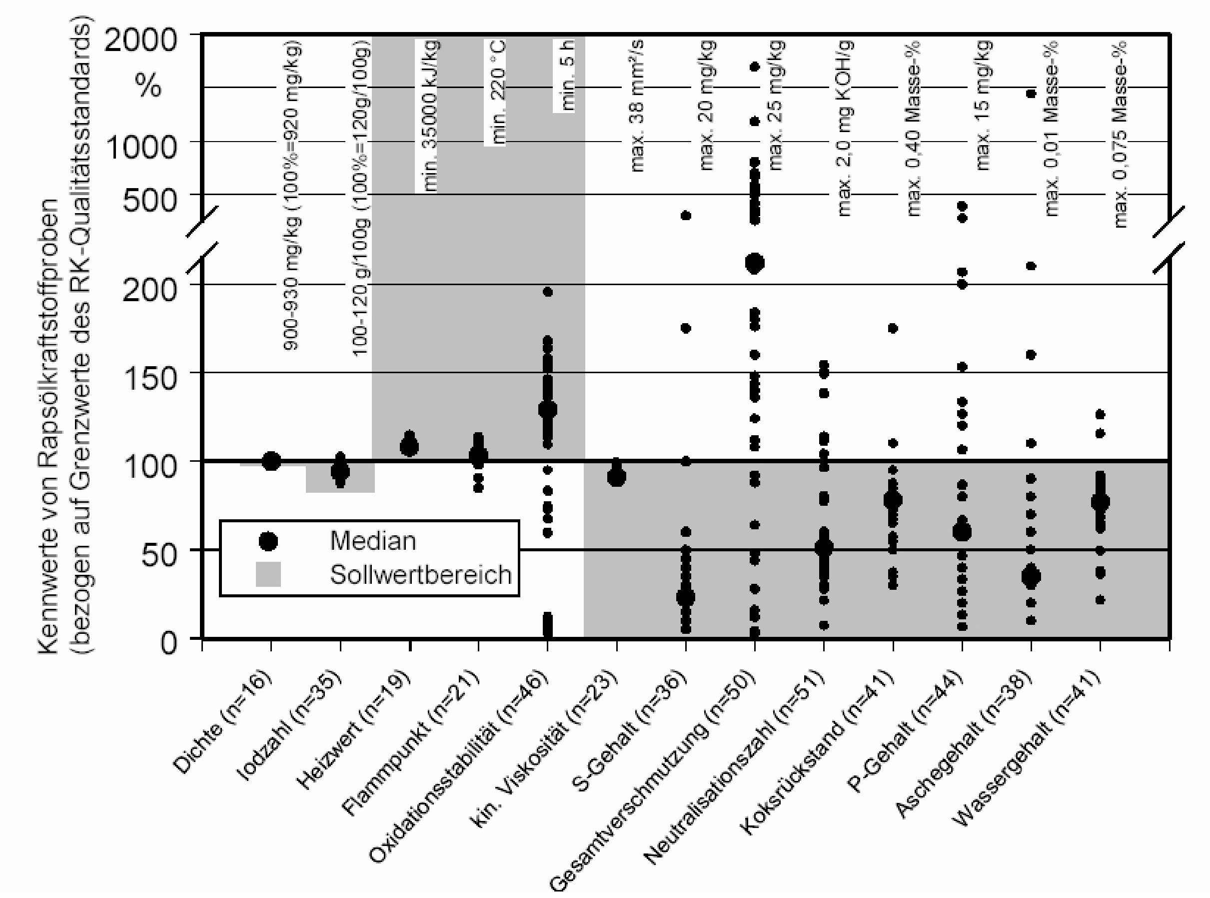


Figure 2-6 Results of quality testing of several rapeseed oil samples; intervals of the results compared to the Weihenstephan (RK 2000) standard

This standard determines nine so-called ‘characteristic’ properties and six ‘variable’ properties of rapeseed oil. The variable properties may be influenced by production, refining, transport and storage of the oil, as opposed to the characteristic properties.

The characteristic properties have been defined as follows:

- Density
- Flash point
- Heat of combustion
- Viscosity

- Cetane number
- Carbon residue
- Iodine number
- Sulphur content

The variable properties are the following:

- Contamination
- Acid value
- Oxidation stability
- Phosphorus content
- Ash content
- Water content

This first, voluntary quality standard (2000) later evolved with minor adaptations into the DIN E 51605 (2005) for vegetable oils as fuel in (converted) Diesel engines. In the next paragraph the mentioned properties are elaborated.

2.2.2.1 Characteristic properties

Density

Density is an absolute relationship between mass and volume at a given temperature. The density gives an indication of other fuel properties, including specific energy and ignition quality.

There is no relation between density and viscosity when different oils are being mixed. There is a correlation between fuel density and NO_x emission: the larger the density, the higher the NO_x-emission will be. The density of vegetable oils is usually around 900 - 950 kg/m^3 and is measured at a temperature of 15 °C.

Flash point

The flash point of a fuel is the lowest temperature at which the fluid gives enough vapour to ignite.

A fluid with a high flash point is usually difficult to ignite. If the flash point is low, explosion risk must be counted with in storage and transport and extra security measures must be taken. Bio-oils have a higher flash point than most kinds of fossil fuels. This means that safety in handling is less of an issue. The table below summarizes some flash points for several vegetable oils.

	Babassu	Castor	Coconut	Corn	Cottonseed	Crambe	Jatropha	Linseed	Olive	Palm	Peanut	Rapeseed	Safflower	High-oleic safflower	Sesame	Soybean	Sunflower	Tallow
Flash point [^{o}C]		260		277	234	274	285	241		280	271	246	260	293	260	254	274	201

Table 2-4 Flash point values for several kinds of oils

The heating value

A fuel's heating value is expressed in MJ/kg. This value depends on the chemical composition and the density of the fuel and is known to vary slightly. A fuel that consists only of carbon and hydrogen atoms will have a higher heating value than a fuel that also contains oxygen or other macro components.

The heating value for bio-oils is usually around 37 MJ/kg. Other types of biological oils (for example, pyrolysis oil) are known to have lower heating values. Fossil fuels like heating oil have an average heating value of about 42 MJ/kg. The heating value is very important for the determination of energy cost in a given application. The price of fuels should not be compared per litre, but per energy content (GJ).Technically the lower energy content of bio-oils makes little difference. Because of the higher density compared to heating oils the fuel volume rate will be about the same. Furthermore nearly all installations can work with a fuel with a 10% lower heating value.

Theoretically all heat that is released upon combustion should be added up to determine the heating value. The fuel's hydrogen will be combusted to water. Usually this water is gaeous in the flue gases because of high temperature. If the flue gases are condensed the released heat may be reclaimed to yield a higher heating value. Difference is hence made between the higher (gross) and the lower (net) heating value. The gross heating value displays the total amount of energy possibly set free. The net heating value gives the combustion energy excluding the condensation energy. This lower heating value is of practical importance, as in most cases the flue gases are not condensed.

Viscosity

Dynamic viscosity is a property displaying the internal resistance of a fluid. Its unit is Ns/m^2. Normally the word viscosity means kinematic viscosity. This is expressed in Stokes, or in SI units m^2/s. The kinematic viscosity equals the dynamic viscosity divided by density, both values must be determined at the same temperature.

$$\nu = \frac{\eta}{\rho}$$

ν = Kinematic viscosity (mm^2/s)
η = Dynamic viscosity (Ns/m^2)
ρ = Density (kg/m^3)

Viscosity plays a large role in the technical application of bio-oils. A high viscosity will hinder the supply of bio-oil to the combustion chamber. Most kinds of bio-oils have a viscosity in the order of 60 – 80 mm^2/s at 20°C. It is a common effect that an oil's viscosity is reduced at elevated temperature (see figure 2-7). Hence fuel heating can provide a solution for application where a low fuel viscosity is demanded, like when atomizing with a nozzle. Considerable changes in viscosity may occur between different types of oils and between bio-oils from different production processes (pressing versus extraction). Some vegetable oils' viscosity values are mentioned in Table 2-5 below.

	Babassu	Castor	Coconut	Corn	Cottonseed	Crambe	Jatropha	Linseed	Olive	Palm	Peanut	Rapeseed	Safflower	High-oleic safflower	Sesame	Soybean	Sunflower	Tallow
Viscositeit op 38 °C [mm^2/s]		297		34,9	33,5	53,6	78,2 (20°C)	27,2		40,2 (40°C)	39,6	37	31,3	41,2	35,5	32,6	37,1	51,15 (40°C)

Table 2-5 Values of viscosity for different kinds of oils

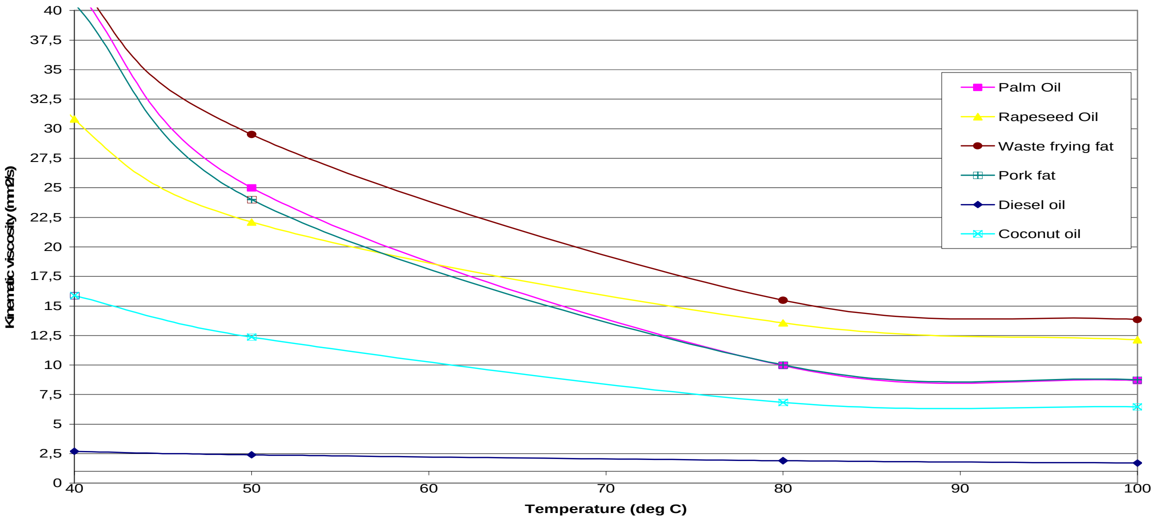


Figure 2-7 Kinematic viscosity against temperature for selected bio-oils

Cetane number

The cetane number is a measure for the ignition properties of a diesel fuel. It is actually a measure of a fuel's ignition delay; the time period between the start of injection and start of combustion (ignition) of the fuel. In a particular diesel engine, higher cetane fuels will have shorter ignition delay periods than lower cetane fuels. The one end reference of the scale, cetane, is an alkane molecule that ignites very easily under compression, so it was assigned a cetane number of 100. The low end reference of the scale is formed by heptamethyl nonane with a cetane number of 15. A diesel fuel's cetane number gives the percentage of cetane in a mixture with heptamethyl nonane that has the same ignition properties. It may be clear that no actual cetane or heptamethyl nonane needs to be present in the fuel tested.

Compared to diesel some kinds of bio-oil have a relatively low cetane number, which may cause ignition problems. This is one of the reasons why diesel engines have to be adapted to use 100% vegetable oil as a fuel. Table 2-6 mentions some cetane numbers for well known vegetable oils. For application outside compression-ignition (Diesel) engines the cetane number is not relevant, hence it can be set aside for the rest of this study.

	Babassu	Castor	Coconut	Corn	Cottonseed	Crambe	Jatropha	Linseed	Olive	Palm	Peanut	Rapeseed	Safflower	High-oleic safflower	Sesame	Soybean	Sunflower	Tallow
Cetaangetal	38			37,6	41,8	44,6	37,8	34,6	60	42	41,8	37,6	41,3	49,1	40,2	37,9	37,1	

Table 2-6 Cetane numbers for some well known vegetable oils

Carbon residue

The carbon residue of a fuel is one the most important oil combustion tests. The carbon residue estimates the combustibility and the tendency to form carbon deposits. In fossil fuels, the asfaltenes are the main cause of bad combustibility. The results of high asfaltene concentrations in fossil diesel fuel in diesel engines can include black smoke, high exhaust temperatures and carbon deposits in the combustion chamber. Usually asfaltenes contain aromatic structures. Asfaltenes may also contain components like sulphur, oxygen, nitrogen and metals (mainly Vanadium and Nickel). Usually the Carbon residue and asfaltenes are related, although the exact relationship varies between different fuels. For bio-oils, the carbon residue is probably correlated with the amount of unwanted polymers within the oil.

Iodine number

The iodine number is a measure for the number of double bonds in the chemical structure of a fat. A high iodine number indicates a large number of double bonds. The occurrence of many double bonds leads to a low melting point of the oil, as displayed in figure 2 7. Hence it is clear from the name that vegetable oils have a higher iodine number than animal fats, that are usually solid at room temperature. Both Coconut oil and Palm kernel oil do not follow the same kind of “trendline” in figure 2.7 which is caused by their relatively high content of C12 fatty acids (see also table 2.5).

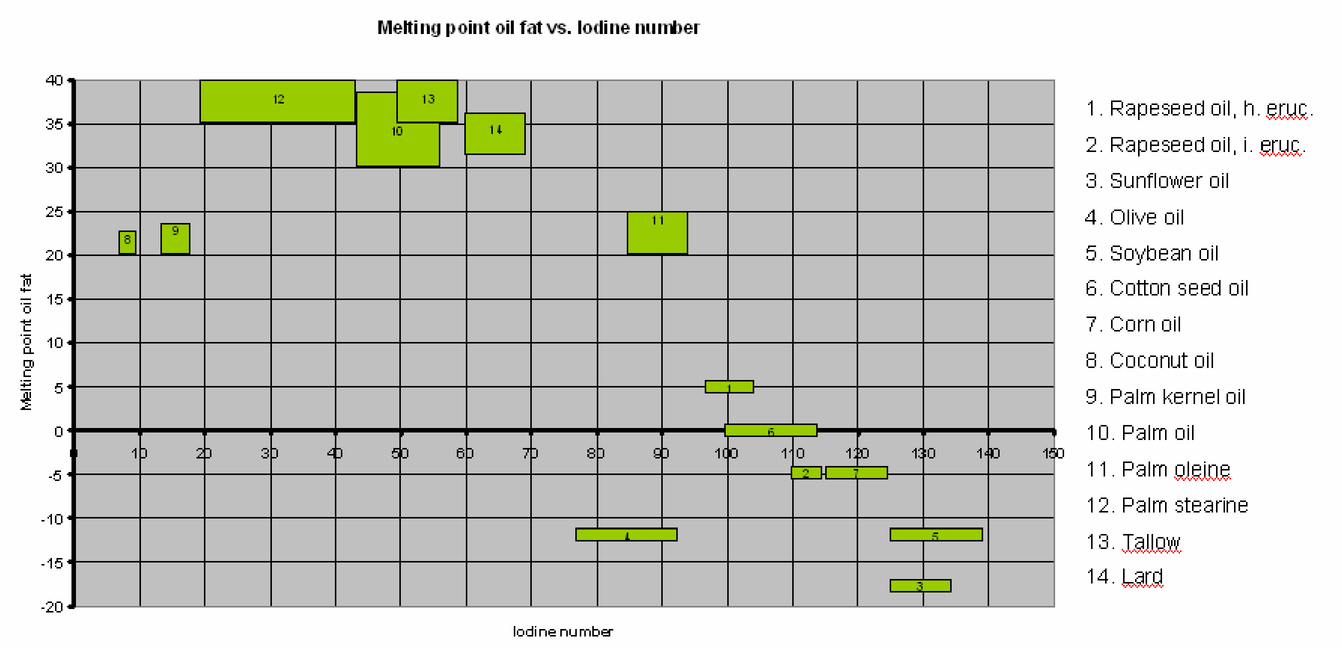


Figure 2-8 Iodine number vs. melting point for various bio-oils (partly from www.journeytoforever.org)

Sulphur content

Sulphur is an element that is naturally present in fossil oil. The sulphur content mainly depends on the oil source and, secondarily, from the refining process. Heavy fuel oil usually has a sulphur content about 2-4 mass%. The formed combustion products of sulphur may lead to a high acidic load on the lubrication oil, to corrosion in the flue gas ducting and to poisoning of eventual $DeNO_x$ and flue gas aftertreatment systems. Bio-oils naturally contain only low quantities of sulphur. Hence fulfilling the requirement for ULSD (ultra low sulphur diesel), 10 mg/kg, usually is no problem and no desulphurisation is required.

2.2.2.2 Variable properties

Contamination

Fine particles present in bio-oil from the production process may clog fuel filters and injectors and cause abrasion all over the fuel circuit. As the amount of contamination is easily controllable by filtering it is important to keep this value as low as possible. Usually, the amount of contamination is correlated with the ash content. In the DIN V 51605 the limit has been set to a maximum of 24 mg/kg, which is easily achievable by filtering the bio-oil.

Acid number

The acid number of a bio-oil expresses the amount of free fatty acids (FFA's) present. Their presence means that triglycerides have dissociated into free fatty acids and remaining components under influence of high temperature, UV radiation, and the presence of oxygen and/or certain metals like copper. It should be considered that those parts that come into contact with the fuel must be acid resistant. Many parts of the fuel system, like injection pumps, nozzles etc. do not resist a high acid content in the fuel. To measure the acid content, KOH is titrated to the fat with phenolphthalein added. At the moment this indicator changes colour the free fatty acids have been neutralised and the neutralisation number (mg KOH/g fat) can be calculated. Usually bio-oils contain more acid components than fossil fuels. This may cause corrosion problems in the fuel system and rapid deterioration of the lubrication in a Diesel engine. The application of corrosion resistant materials can solve this issue but leads to extra investments.

Oxidation stability

The oxidation stability is related to the shelf life of a bio-oil. Oils with a high iodine number, and hence a lot of unsaturated fatty acids, suffer from more problems with this parameter than low-iodine, saturated oils. Again the oxidation stability can be influenced by unfavourable storage conditions, high temperature, water and the presence of certain metals like copper. As the age of an oil increases, its viscosity increases as well. The DIN V 51605 limits the oxidation stability to a minimum of 5 hours at a temperature of 110°C. It is tested by bringing a sample of the oil to this temperature, leading air through it and measuring the conductivity. At the moment the conductivity suddenly rises, many oxidation products have been formed and the limit has been reached.

Phosphorus content

Bio-oils naturally contain phosphorus. In vegetable material this occurs in the form of phospholipids originating from the cell walls. In animal fat the phosphorus may come from the bones, phosphated sugars, the body's energy transmitters (ADP/ATP) or even DNA, depending on the processing technology. The presence of excessive phosphorus in the fuel leads to abrasive fouling in the combustion chamber. Furthermore the phosphorus in vegetable oil is usually present in slimy

components (‘gums’) that can lead to obstructions in the fuel system (clogging of fuel filters). Besides a high phosphorus content of vegetable oil is known to depress its oxidation stability.
In the DIN V 51605 a maximum of 12 mg/kg P is allowed. This means that most bio-oils will have to be refined before use as a fuel for a Diesel engine.

Ash content

The ash content is related to inorganic substances in the fuel. The amount of ash in the fuel is partially related to the total contamination value. Contaminations can come into the fuel in various stages of processing, storage or transport. Frequently found elements are: phosphorus (P), calcium (Ca), silicium (Si), magnesium (Mg), sodium (Na), potassium (K) and zinc (Zn). The ash content indicates the amount of abrasion material in the fuel. It can work harmfully on the fuel system and the combustion chamber. In animal fat the ash content correlates with about 50% of the total contamination number. The DIN V 51605 specifies a maximum of 0,01 mass% of ash.

Water content

Water is the most frequent contamination of the fuel. Too high water content contributes to the formation of free fatty acids. Water can reach the fuel in various ways. Examples are leaks, condensation etc. Normally a separator is included in the fuel preparation street to eliminate the water from the fuel. A small amount of emulgated water could be positive in that it can lead to cooler combustion and hence reduction of NO_x emissions. But presence of water decreases the energy content of the biofuel: it can be estimated that every volume% of water decreases the heating value with 1%. As a Diesel injection system works with high pressures that are highly variable over time water can give rise to cavitation and hence damage in the injection system. For bio-oil the water content is less critical than for conventional diesel fuels but water layers can provoke microbial deterioration of the fuel during storage and transport. The DIN V 51605 gives a maximum of 0,075 mass% water for bio-oil.

2.3 Some remarks about other bio fuels

2.3.1 Glycerine

Glycerine is a by-product from biodiesel production plants and amounts to around 11 w-% of the total biodiesel produced. Figure 2-9 shows a schematic of the biodiesel process where animal fat or vegetable oil (see also figure 2-2 for the general structure of a fat or oil) are transesterified with methanol into biodiesel with glycerin as a residue and with potassium hydroxide as a catalyst.

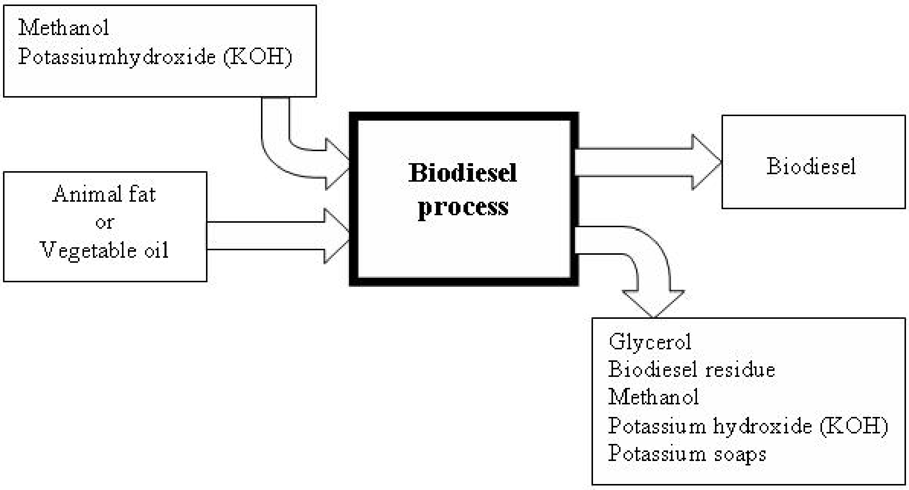


Figure 2-9 Process chart of biodiesel production

Glycerine (also referred to as glycerin = C_3H_6O) is on the list (NTA nr. 544) of biofuels of CertiQ, the notified body of the Dutch government for the “ MEP”-subsidy, a subsidy for CO_2-neutral generated electricity. Current EU-27 biodiesel production amounts to around 5 Mtonnes which equals a glycerine production of around 550 ktonnes on a yearly basis. Given the current political efforts to decrease CO_2-emissions, it is to be expected that biodiesel production and inherent glycerine production will rise in the near future. Germany, Austria and Spain already have a more extensive bio diesel production. The byproduct of the biodiesel proces is in not pure glycerine but in fact a mixture which consists of:

- 60% glycerine
- 15% biodiesel residue

- 12% alkaline: potassium hydroxide and potassium soaps
- 10% methanol
- 3% other (ashes)

This mixture is often referred to as crude glycerin. Besides glycerin and catalysts, crude glycerin also contains bio diesel because it is difficult to separate all the bio diesel from the crude glycerin without contaminating it with traces of the crude glycerin mixture. It has to be noted that the percentages of the above can vary for different bio diesel producers and different inputs of the bio diesel production process (e.g. animal fat or vegetable oil). The crude glycerin can be refined to crude glycerine that can have a purity of around 50-85% (the remainder is water), and may contain around 3 w-% of ashes. The methanol can be separated from the crude glycerin quite easily and economically by heating it up to the boiling temperature of methanol (65°C); however the separation of alkaline is an economically less attractive process. This crude glycerine can then be refined with absorption technologies (carbon, bleaching earth) and fractional distillation at around 250°C in order to have a purity of 99%. The heating value of crude glycerin is on average about 18 MJ/kg and the heating value of pure glycerine is 16 MJ/kg. These are relatively low heating values compared to other bio fuels, however crude glycerin and glycerine can be burned as a fuel in boiler burners or gas turbine combustors that are properly adapted for this purpose (see also chapter 5). From an economical point of view, crude glycerin (without methanol) is very attractive, it is however heavily polluted with alkaline and ashes (total of 10%). Pure glycerine is more attractive from a technical point of view because it is not polluted, but it is far more expensive than crude glycerin.

2.3.2 Biogas from digestion

Table 2-7 gives an indication on what kind of limits may be expected for biogas from digestion in stationary gas turbines.

Table 2-7 Indication of possible requirements for biogas from digestion

Characteristic	**Limit range indication**
LHV	f.i. 20-40 MJ/m^3
Change in LHV	f.i. 4% / 10 minutes
H2S	f.i. 150-2000 mg/m^3?
NH3	f.i. <100 mg/m^3

Dust	f.i. < 30 mg/m^3 (<10 mu)
Moisture content	f.i.
Siloxanes	f.i. 1-20 ppm

2.3.3 Fast pyrolysis oils

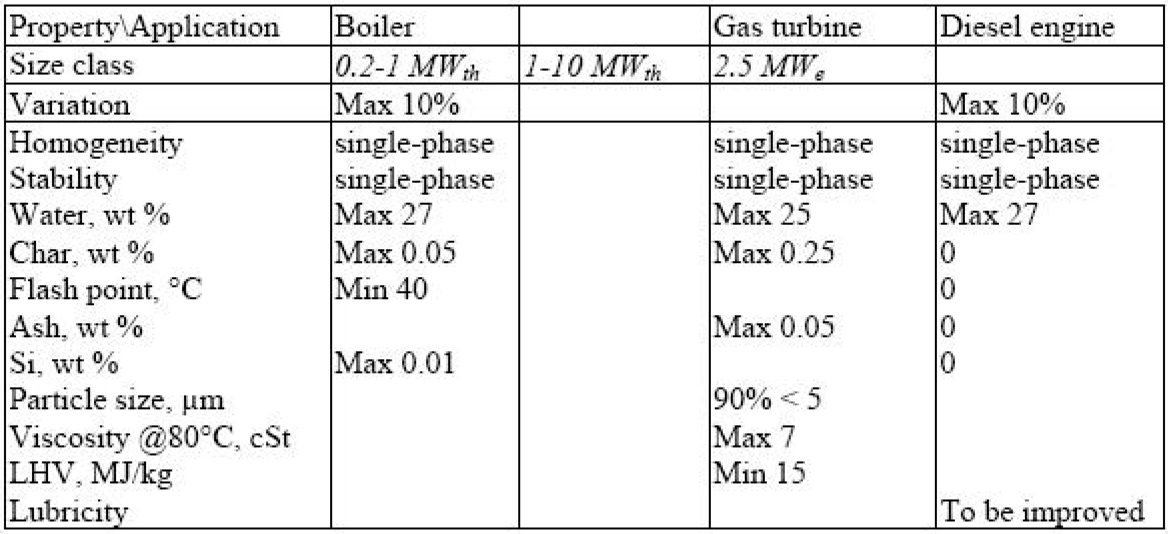
Table 2-8 Pyrolysis bio-oil requirements set up by Orenda for their OGT 2500 kWe gas turbine (taken from Thermonet PyNe)

ID	Fuel Parameter	**Test Method**	**Units**	**Guidelines**
1.	Low Heating Value	ASTM D240/5291	MJ/kg	15-25
2.	Pour Point. Max	ASTM D97	°C	15
3.	Kinematic Viscosity at 80°C	ASTM D445 mod.	cSt	4-7
4.	Surface Tension at 80°C, Max	D971 mod.	MN/m	30
5.	Specific Analysis, max Na+K Ca V Pb Cl S Ash	AA^a or ICP “ “ “ “ ASTM D240 ASTM D4294 ASTM D482	ppm$_w$ ppm$_w$ ppm$_w$ ppm$_w$ ppm$_w$ wt% wt%	5 5 3 5 1 .02 0.05
6.	Density @ 80°C, max	ASTM D4052	g/ml	1.20
7.	Solids Content greater than 0.1µm, max (Note: 90% solids should be less than 5.0µm in size)	ASTM D2276 (Millipore Membrane Filtration)	Wt%	0.25
8.	pH	Accumet 925 pH meter	pH	2.5-7.0

9.	Thermal Stability: Exposure for 24 hrs @ 80°C Parameters @ 80°C: i) Solids creation, max ii) Viscosity, max iii) Phase stability	NA	wt%	i) 0.1 wt% increase in solids content. ii) 5% increase in viscosity iii) no phase separation permitted.
10.	Water content	ASTM D95 followed by D1744	wt%	15-25
11.	Ramsbottom Carbon Residue on 10% Distillation residue, max	ASTM D5245	wt%	10

Quite some research has been performed into the quality and application of fast pyrolysis oils. Gas turbine and stationary engine tests have also been executed. The gas turbine tests were performed by a Canadian company called Orenda. Fast pyrolysis oils do have, by their nature, some disadvantages like high acidity, a low heating value and high moisture content.

Table 2-9 General fast pyrolysis bio-oil requirements as set up by Thermonet PyNe (Altener II)



Property\Application	Boiler		Gas turbine	Diesel engine
Size class	$0.2\text{-}1\ MW_{th}$	$1\text{-}10\ MW_{th}$	$2.5\ MW_e$	
Variation	Max 10%			Max 10%
Homogeneity	single-phase		single-phase	single-phase
Stability	single-phase		single-phase	single-phase
Water, wt %	Max 27		Max 25	Max 27
Char, wt %	Max 0.05		Max 0.25	0
Flash point, °C	Min 40			0
Ash, wt %			Max 0.05	0
Si, wt %	Max 0.01			0
Particle size, µm			90% < 5	
Viscosity @80°C, cSt			Max 7	
LHV, MJ/kg			Min 15	
Lubricity				To be improved

Table 2-10 Operational problems in boilers, engines and gas turbines depending on pyrolysis oil characteristics (Thermonet PyNe)

Property	**Specification to be met**	**Current value**	**Problem**	**Solution**
Variation	Max 10%	> 50%	Changes in feed and in process parameters	Quality control system
Water	< 27 wt%	18-40	Inhomogeneity, phase separation (> 30 wt% water)	Feedstock drying Increase (< 50 °C) of condensation temperature
Solids	< 0.01wt%	= 0.5 wt%	Wear of injectors Increased liquids instability High CO emissions	Homogenous particle size distribution of the feed Hot vapour filter Three cyclones on reactor exit Liquids filtration/centrifugation
Ash	< 0.01 wt%	< 0.1 wt%		Feedstock choice Hot vapour filter Three cyclones on reactor exit Liquids filtration/centrifugation
Homogenity	Single-phase	Variation	Uneven liquid quality	Feedstock moisture < 12 wt% Liquid water content < 27 wt%
Stability	Max 100% visc. Increase (24h 80°C, visc. measurement 40°C)	50-150%	Changes in liquid properties during storage and use	Alcohol addition
Flash point	Depends on country	> 40 °C	Safety regulations for transportation	Adjusting the liquid condensation temperature
pH	FDS	2-3	Corrosion of fuel lines	All pipework, vessels, and gaskets must be acid resistant
LHV	FDS	16-19 MJ/kg	50% lower than fuel oil Does not auto-ignite at start-up	Increase pump pressure to injectors Increase diameter of fuel lines Dual fuelling required (%)

Viscosity	FDS	> 50 cSt @20°C	Too high for most fuel injectors	Preheat liquids to reduce viscosity Add co-solvent (alcohol) Use of emulsions
Lubricity	FDS	Not determined	Build up of lacquer on the injection needle and fuel pump plunger	Lubricity/flow properties improvement Additives

FDS = Cannot be influenced/specified. Value to be included in Fuel Data Sheet

3 Fuel quality demands and refining

3.1 Conventional fossil fuel treatment steps for combustion engines

A very common fuel treatment for heavy fuel oil or f.i. crude oil plant may look like the photo below. The purpose is to reduce harmful contaminants such as sodium, potassium, calcium, magnesium, vanadium and lead, from heavy fuel oil, crude oil, crude blends, residual fuels, aero-derivative fuel, No. 2 distillates such as diesel and petroleum naphtha.

Figure 3-1: Fuel oil treatment plant using AlfaLaval centrifuges [www.marstechusa.com]

Sometimes also water washing (60°C) with centrifuging afterwards may be used in order to reduce water soluble potassium and sodium down to the right specifications (f.i. in the GT 1 and 2 these are very stringent). Ash-bearing fuels include unrefined crude oil, residual oils from the refining process and contaminated refined fuels. Crude oil naturally contains oil-soluble vanadium, nickel and sulphur compounds. Water soluble sodium, potassium and calcium compounds occur naturally in water produced with crude oil and from contamination during transportation.

The major contributor to low melting ash is vanadium, ranging from <1 to >500 ppm. Sulphur is found at varying levels up to 5%. Water soluble salts of sodium, potassium and calcium are found at varying levels depending on the history of the fuel.

Vanadium pentoxide melts at 680°C. Eutectics formed from combinations of sodium, potassium and calcium with vanadium, lead and sulphur have lower melting points in the 500-600°C range. Deposits resulting from this ash foul the power section blades and vanes and are catastrophically corrosive above their melting points. The problem is controlled by eliminating and modifying the ash to higher melting species which do not adhere to hot path parts.

Ash-bearing fuels are usually treated with water to form emulsions. The emulsions are broken in centrifuges or electrostatic separators with the aid of chemical demulsifiers to remove most of the water soluble salts of sodium, potassium and calcium. The usual specification for sodium plus potassium in gas turbine fuel is <0,5 – 1 ppm. Magnesium is then introduced into the fuel, generally at a 3 to 1 weight ratio to the vanadium. This converts vanadium into $Mg_3V_2O_8$ which melts at 1.000°C, well above the temperature of the metal parts. The ash passes through the machine without depositing or corroding the hot path area.

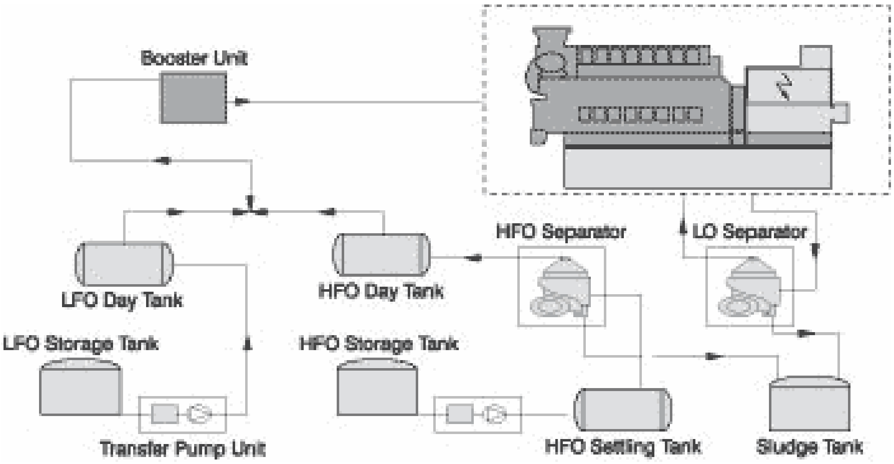


Figure 3-2: A very common fuel treatment system for heavy fuel oils in front of a diesel engine

The following section gives an explanation of a common fuel treatment system including settling tanks and the fuel centrifuge (partly taken from www.kittiwake.com).

Settling Tank

The effectiveness of a settling tank depends on a number of factors. At the design stage, the number of tanks, size and height will affect the effectiveness for the removal of either water or solids. Many installations only have one settling tank fitted and this factor reduces the residence time of the fuel within the tank. To an extent, the residence time can be increased by increasing the size of the tank.

Operationally, the effectiveness is determined by the viscosity of the fuel bunkered and the temperature at which the tank is maintained. It can be shown from Stokes' Law that the greater the viscosity, the slower is the rate of settling for water or dirt within the fuel. By heating the tank, the viscosity is reduced and it is usual to maintain a temperature of 50°C or 10°C below the flash point.

Fuel Centrifuges

The correct sizing of the fuel centrifuges depends on the daily fuel consumption and on the design viscosity of the system. As a matter of prudence, many centrifuges are designed for a fuel of 700 cSt at 50°C. This fuel is the maximum specified in accepted fuel standards, such as ISO 8217. In actual service, the fuel used is more typically IF180 or IF380 (180-380 Cst @ 50°C). The reality is that under these conditions it is oversized and theoretically operates more effectively.

Basically, there are two different types of centrifuge which are installed and found in engine plant. Those of what may be described as the "traditional" design have a density limit of 991 kg/m^3 (0,991 kg/l) at 15°C. In such instances, it is usual to fit three machines; two in use and one as a stand by unit. Over the years, the consistent recommendation has been that in normal circumstances, two machines are run in series, with one as a purifier and the other as a clarifier. The purifier, for the removal of water and solids, is situated before the clarifier which primarily removes solids.

High specific gravity fuels and fuels containing catalytic fines require separation at the highest temperature, 98°C, to reduce the viscosity as much as possible, and reduction of throughput as efficiency increases with decreasing flow rate.

Parallel operation of both the main and standby separators provides good pre-treatment of fuels but has proved to be slightly less efficient than series-operated separators when dealing with modern day fuels. Parallel operation in the clarifier mode with lowest possible throughput is the most effective method of treating fuel contaminated with cat fines and only traces of water content.

The other type of machine is able to operate effectively on fuels up to 1010 kg/m^3 at 15°C. In this case, normally only two machines are fitted: one in operation with the other on standby.

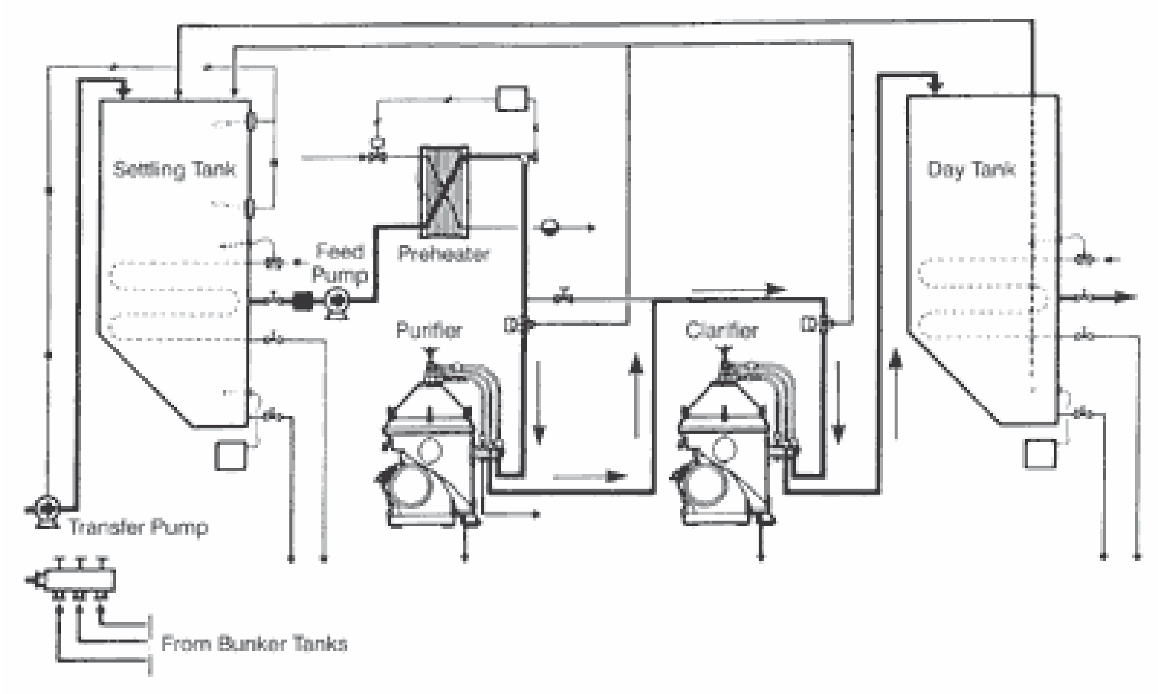


Figure 3-3: A very common fuel treatment system for heavy fuel oils (www.kittiwake.com)

3.2 Bio-oil treatment for combustion engines

Similar to the conventional heavy fuel oil treatment, bio-oil also has to be filtered and may also go through centrifuges just before entering the combustion engine. The filtration of bio-oils is extremely important as filtration, generally speaking, lowers the dirt / contamination and ash content. Even though the bio-oil may be in compliance with the specifications of the engine manufacturer after leaving the plant oil refinery / crusher, contamination may take place during transport and storage.

Refining processes for bio-oils are particularly aimed at the removal of phospholipids and free fatty acids and are discussed later (paragraph 3.5).

Bio-oils are vulnerable towards oxidation when stored and/or filtered at temperatures above 40°C when air – oil contact takes place. Figure 3-4 shows the negative impact of oxidation reactions during hot filtration when no nitrogen shield is implemented in the oil treatment / storage system. The oxidation stability decreases towards less than 1 hour while also unwanted polymerisation and/or decreases of unsaturated bonds take place (figure 3-4).

Figure 3-4 Example of extensive bio-oil filtration without N-shielding (thermal oxidation effects)

3.3 Bio-oil quality demands for stationary engines

In the table below the fuel requirements issued by several important standards and engine suppliers were summarized.

Limiting parameter	Unit	DIN 51605		Weihenstephan		SKL (Veg. oil)	ABC (Bio-diesel)		MAN B&W	Kuhse	Wärtsilä
		Min.	Max.	Min.	Max.		Min.	Max.			
Density (15ºC)	kg/m^3	900	930	900	930	= 930	850	990	≤ 991	900 - 930	≤ 991
Flash point	°C	220		220		> 200	100		≥ 60	> 220	≥ 60
Calorific value	kJ/kg	36000		35000		> 35000	37000	43000	37000	> 36000	
pH									5 to 8		
Kinematic viscosity (40ºC)	mm^2/s		36		38		0,02	38		< 34	< 24
Kinematic viscosity (50ºC)	mm^2/s					= 30					
Kinematic viscosity (70ºC)	mm^2/s					= 20					
Kinematic viscosity (80ºC)	mm^2/s								< 11-18		
Pour point	°C					< 40			≤ 30		
Cetane number		39				> 35	51		> 30	39	
Conradson carbon residue	wt%		0,40		0,40			0,3	0,1	< 0,40	
Iodine number	g/100g	95	125	100	120					95 - 125	< 120
Sulphur content (S)	mg/kg		10		20	< 50		50	< 10	< 8	< 50
Total contamination	mg/kg		24		25	< 50				< 10	
Acid number	mg KOH/g		2,0		2,0	< 3		4	< 40	< 1,5	< 5,0
Oxidation stability	h	6,0		5,0		> 5				< 6	
Phosphorus content (P)	mg/kg		12		15	< 30		10	< 30	< 8	< 100
Ash content	wt%		0,01		0,01	< 0,1		0,05	< 0,1	< 0,01	< 0,05
Particle size	µm								< 20		
Water content	wt%		0,075		0,075	= 0,100		0,05	< 0,5	< 0,075	0,2
Magnesium + Calcium (Mg+Ca)	mg/kg		20							< 20	
Free fatty acids (FFA)	wt%					< 1,5			15-20%		
Vanadium (V)	mg/kg							50	< 10		
Calcium (Ca)	mg/kg							50			
Silicium (Si)	mg/kg							10			< 10
Sodium (Na)	mg/kg							< 30% V	< 100		
Sodium + Calcium (Na+Ca)	mg/kg							30			< 30
Aluminium	mg/kg							50			
Aluminium + Silicium (Al+Si)	mg/kg								< 25		
Polymer	%							2			
Nitrogen (N)	mg/kg					< 10					

Table 3-1: Overview of fuel requirements for different standards and diesel engine manufacturers

3.4 Bio-oil quality demands for stationary gas turbines

Based upon the ASTM diesel standard, OEM gas turbine and engine specs, the Thermonet-R&D and our own research and interpretations, we propose the following bio-oil quality requirements (also depending on design fuel specifications of the gas turbine).

	Heavy industrial gas turbines (designed for GT 3, HFO) e.g. Siemens, GE, Hitachi, Orenda	Aeroderivitive (designed for GT1 & 2) e.g. LM 2500, Rolls Royce
Total ash	0,05%	0,01%
Total contamination	0,10%	0,05% (incl. Water)
Viscosity	<10 cSt @ 80°C	<8 cSt @ 80°C
P	5 mg/kg	
S	1 wt%	
Na + K	5 mg/kg	1 mg/kg
Free Fatty Acids	1 wt%	1 wt%
Conradson carbon residue	0,5%	0,35%
Filtration at	5 mu	

Table 3-2: Overview of proposed fuel requirements for bio-oil in stationary gas turbines

3.5 Refining of bio-oil

The table on the previous page briefly summarizes the fuel requirements according to several engine manufacturers (see Table 3-1). Bio-oil will have to be refined to comply with these standards. This refining can follow two different routes, being chemical (alkali) refining and physical refining (see Figure 3-4 below).

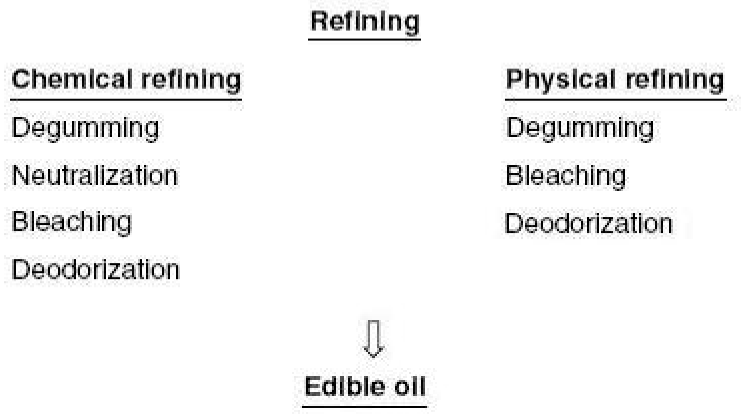


Figure 3-5: Chemical and physical refining

It is how the majority of the FFA’s is removed that makes the essential difference between these routes. In chemical refining most of the FFA’s are removed in the form of soap after neutralising the oil with lye. In physical refining most of the FFA’s are removed with steam in the deodorization step.

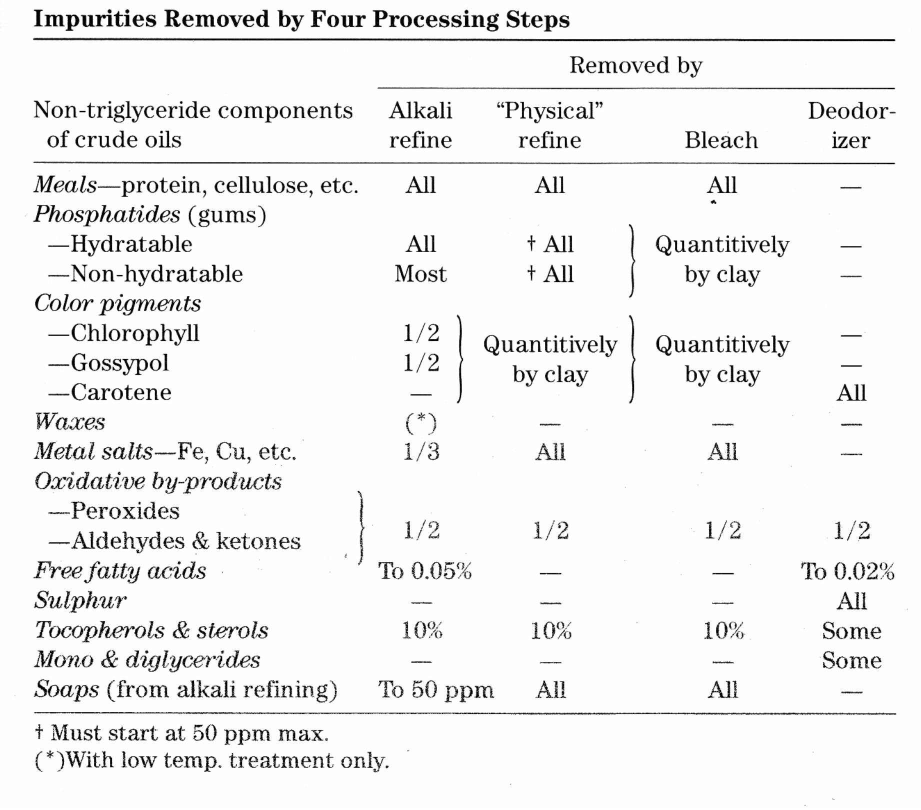
3.5.1 Chemical refining

Chemical refining, also called alkali refining, is a strong tool. It works on all the undesirable, non-triglyceride components except carotene and sulphur, and both of these are easily handled in the deodorizing step. Alkali refining is the only process, except deodorizing, that removes FFA’s.
First degumming is performed to reduce the content of phosphorus and metals. Depending on the desired end product water or acid is added. The precipitated gums are removed with a centrifuge. The next step is neutralising. Herein most of the FFA’s are removed by converting them to soap with lye. Then bleaching earth or active carbon is added in the bleaching step to remove the last traces of metals or soap from the oil. Afterwards the oil is led through a deodorizer. This steam-driven process reduces the content of sulphur and aldehydes and ketones. A drawback of this method is a considerable loss of bio-oil because of soap formation in the neutralisation step. Hence the efficiency of this method is limited.

3.5.2 Physical refining

Physical refining is a treatment that removes the FFA’s in the deodorizing step instead of using lye. The process contains the same steps as described above, only the neutralisation step fails.
First degumming is performed to reduce the contents of phosphorus and metals. In this step water of acid is added, again this depends on the desired final product quality. The precipitated gums are removed using a centrifuge. Afterwards no caustic neutralisation is done like in chemical refining, but instead bleaching earth or active carbon is added directly to the degummed oil. Then the oil is passed through a deodorizer where the majority of the FFA’s is removed. Furthermore, the deodorizing reduces the oil’s content of sulphur and aldehydes and ketones with the help of steam.

Table 3-3 Removal of several impurities by different refining steps [Wan]



Impurities Removed by Four Processing Steps

	Removed by			
Non-triglyceride components of crude oils	Alkali refine	“Physical” refine	Bleach	Deodor-izer
Meals—protein, cellulose, etc.	All	All	All	—
Phosphatides (gums)				
—Hydratable	All	† All	Quantitively by clay	—
—Non-hydratable	Most	† All		—
Color pigments				
—Chlorophyll	1/2	Quantitively by clay	Quantitively by clay	—
—Gossypol	1/2			—
—Carotene	—			All
Waxes	(*)	—	—	—
Metal salts—Fe, Cu, etc.	1/3	All	All	—
Oxidative by-products				
—Peroxides	1/2	1/2	1/2	1/2
—Aldehydes & ketones				
Free fatty acids	To 0.05%	—	—	To 0.02%
Sulphur	—	—	—	All
Tocopherols & sterols	10%	10%	10%	Some
Mono & diglycerides	—	—	—	Some
Soaps (from alkali refining)	To 50 ppm	All	All	—

† Must start at 50 ppm max.
(*)With low temp. treatment only.

3.5.3 Degumming

Degumming is a process step that reduces the phosphorus content and removes metals from the oil or fat. It is a major step in the refining process. Phosphorus is removed from the oil because it may give trouble in deodorizing and because it is an unwanted component which may cause polymerisation (see section 2.2.2.2). The metals are removed because they can impair the shelf life of the oil and also because their presence in the final product is not desired. Table 3-4 gives a summary of naturally occurring phosphorus contents of several different oils.

Table 3-4 Natural phosphorus content in various crude vegetable oils [Logan]

Oil type	**Phosphatides (%)**	**Phosphorus (ppm)**
Coconut	0,02 – 0,05	10 – 20
Corn	0,7 – 2,0	250 – 800
Cottonseed	1,0 – 2,5	400 – 1000
Groundnut	0,3 – 0,7	100 – 300
Palm	0,03 – 0,1	15 – 30
Rapeseed	0,5 – 3,5	200 – 1400
Soya	1,0 – 3,0	400 – 1200
Sunflower	0,5 – 1,3	200 – 500

Phospholipids occur as micelles in the oil because a polar main group. A part of the phospholipids present binds with metal ions, causing the necessity to add acid for their removal instead of only water. Vegetable oil should have a P content of max. 100 – 150 ppm before being processed in a refinery like that at Electrawinds (Belgium) or SRC (Amsterdam). For deodorising, a maximum of 30 ppm of P is allowed in the oil, whereas the final product may contain a maximum of 3 -20 ppm of P.

3.5.3.1 Phospholipids in oil

Raw vegetable oil contains different types of phospholipids that may amount to up to 2 weight percent. Below the most important phospholipids in soy oil are summed up:

30% phosphatidyl choline	(PC)
30% phoshpatidyl ethanolamine	(PE)
25% phoshpatidyl inositol	(PI)
15% phosphatidic acid	(PA)

Figure 3-5 below shows the structural formula of the most important phospholipids.

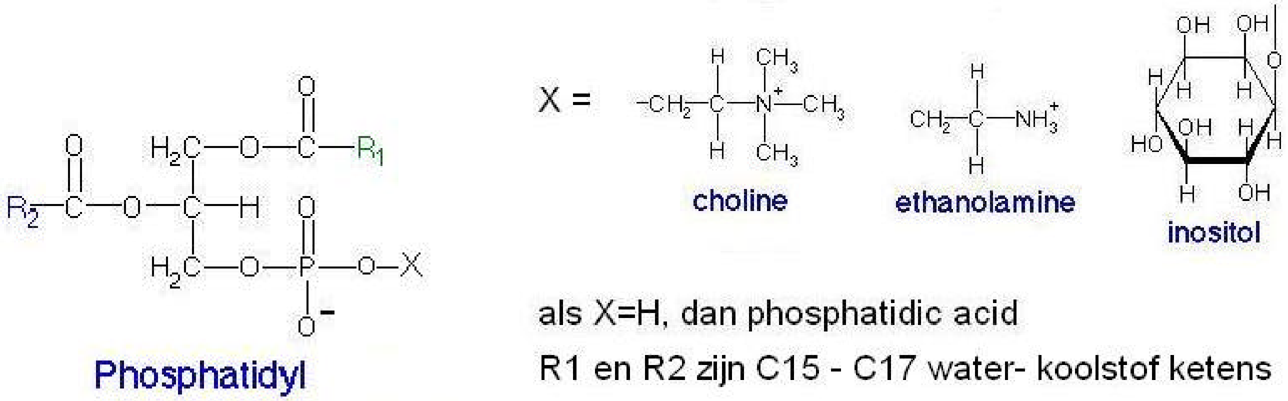


Figure 3-6 Structure formulae of phospholipids

Phospholipids are divided into two groups, hydrating and non-hydrating phospholipids. Those that contain a strong polar group, like choline, are hydrating. These are removed with addition of water. The non-hydrating phospholipids, also called NHP's, are bound to a metal ion, usually Ca or Mg. First this bond has to be broken before they will dissolve into water. This bond can be broken with an acid like citric acid that is stronger than phosphatic acid.

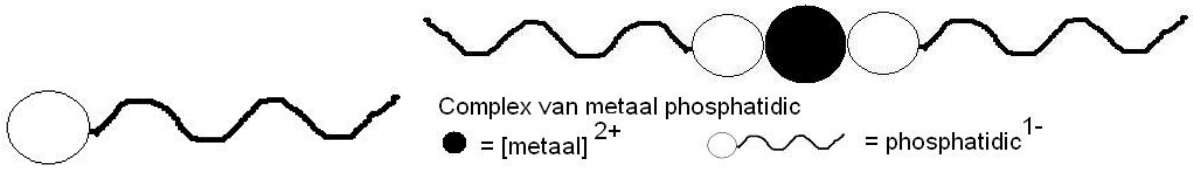


Figure 3-7 Hydrating and non-hydrating phospholipids

3.5.3.2 Degumming mechanism

Figure 3-7 below shows an example mechanism of an acid degumming with citric acid (Cit). The mechanism is based on the assumption that all reactions take place in the aqueous phase.

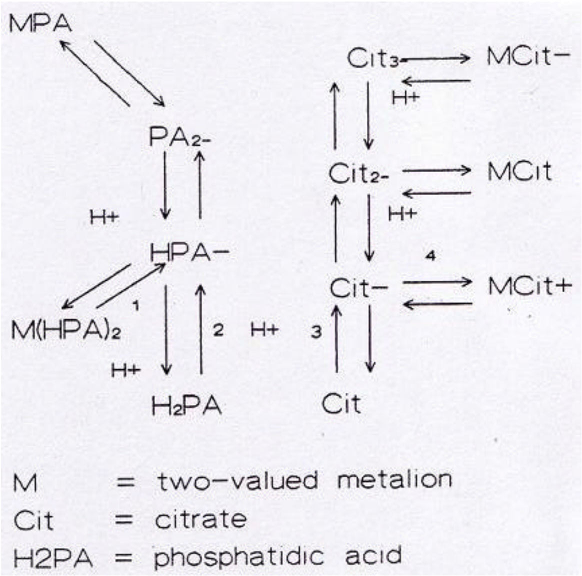


Figure 3-8 Degumming mechanism

In the first step the metal ion is removed from the phosphatic acid. This requires a low pH value, provided by the citric acid that is added. At the same moment the citric acid binds a complex with Ca and Mg (step 3). To prevent the citric acid from protoning itself the pH value may not sink below 0,9. In step 4 the metal is rendered insoluble.

The amount of acid to be added, in this case citric acid, must be about twice as large as the amount of bivalent metal in the oil. After the acid, water is added. It has a hydrating effect and furthermore it increases the pH value. The pH value must be above 1,8 to give complete separation of the phosphatidic acid from the oil.

The water penetrates into the micelles, causing an increase in the particle size which allows filtration to separate the particles. Figure 3-8 schematically shows how non-hydrating phospholipids are made hydrating. This is the essence of acid degumming.

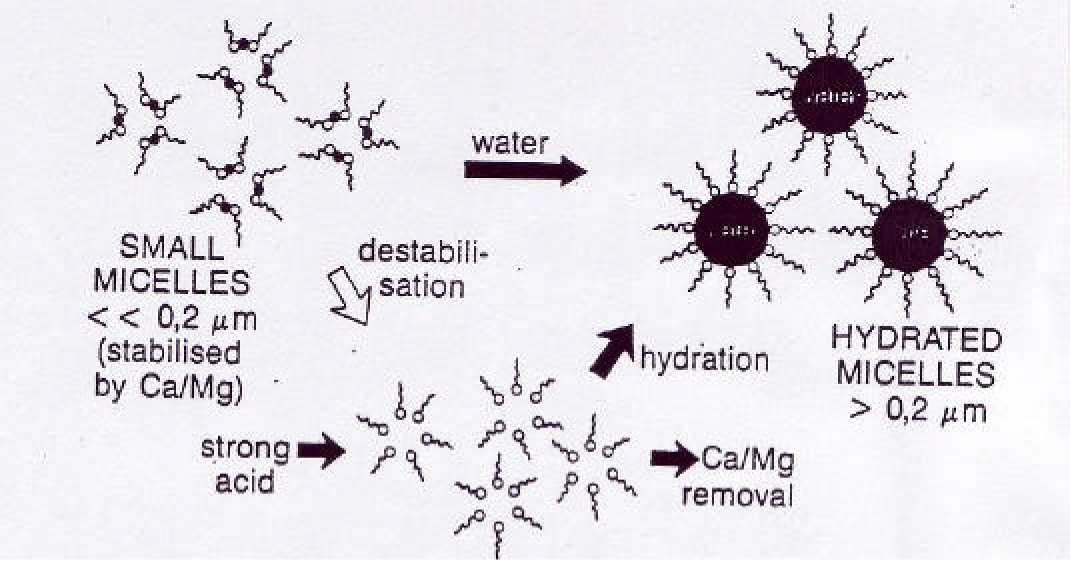


Figure 3-9 Hydration of phospholipids

3.5.3.3 Dry degumming (Acid Conditioning)

Acid conditioning is also known as acid preparation or dry degumming. It is primarily used for processing oil and fat with a low initial gum content.

An acid, like citric or phosphoric acid, is mixed to the oil at a temperature of 60 – 70°C. The amount of acid used usually ranges between 0,05 – 0,2 mass%. Citric acid is slightly more expensive than phosphoric acid but is more effective in the removal of non-hydrating phospholipids. Heating of raw rapeseed oil with 0,1 mass% of citric acid to 70°C can result in oil with only 2 mg/kg phosphorus and 0,3 mg/kg Fe after separation of the gums. The conditioned oil is sent straight to the bleaching step. After the bleaching step, which is elaborated in the remainder of this chapter, the oil is separated from the precipitated gums using a centrifuge.

An important aspect in the acid conditioning is intensive stirring after addition of the acid. In that case the required retention time at 60 – 70°C will be about one minute. Methods based on slow stirring require about 20 minutes retention time and need more acid.

3.5.3.4 Water degumming (water washing)

In water degumming hot water is mixed to the oil at about 60 – 70°C. Hydrating phospholipids absorb water and precipitate as a gum phase. After precipitation this gum phase can easily be separated from the oil. This treatment can remove 99% of phospholipids from certain vegetable oils. A disadvantage is the inability of this method to remove non-hydrating phospholipids, which limits the suitability of water degumming. Oils that have been water degummed usually have a phosphorous content between 50 and 200 ppm. In Figure 3-9 the water degumming process scheme is depicted.

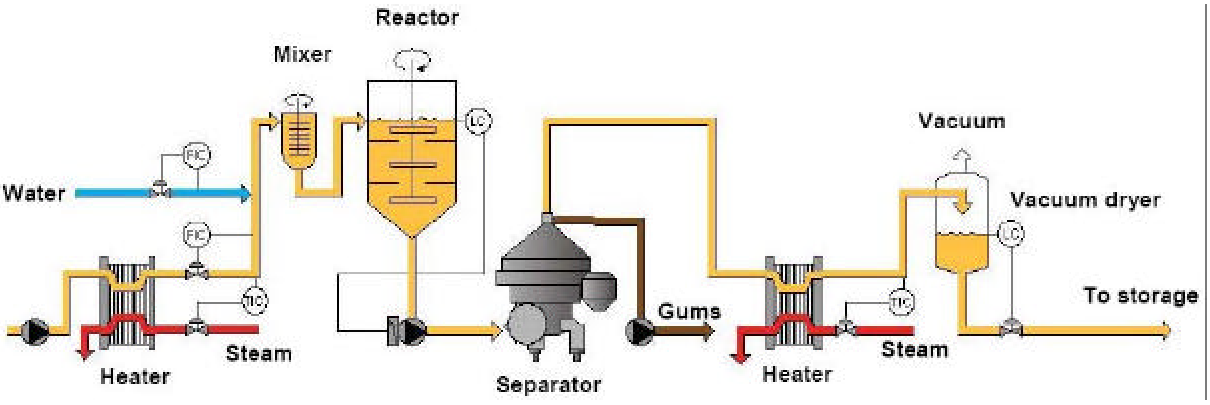


Figure 3-10 Process scheme of water degumming [Logan]

3.5.3.5 Acid Degumming

Acid degumming is more effective when it comes to removal of non-hydrating phospholipids. Its mechanism has been discussed earlier in this chapter. This method is applied instead of acid conditioning in case of high initial gum concentrations. The oil centrifuged prior to transport to the bleaching step. For the rest the application is identical to acid conditioning. After acid degumming the oil produced usually has a phosphorus content between 20 and 50 ppm. Figure 3-10 displays the acid degumming process scheme.

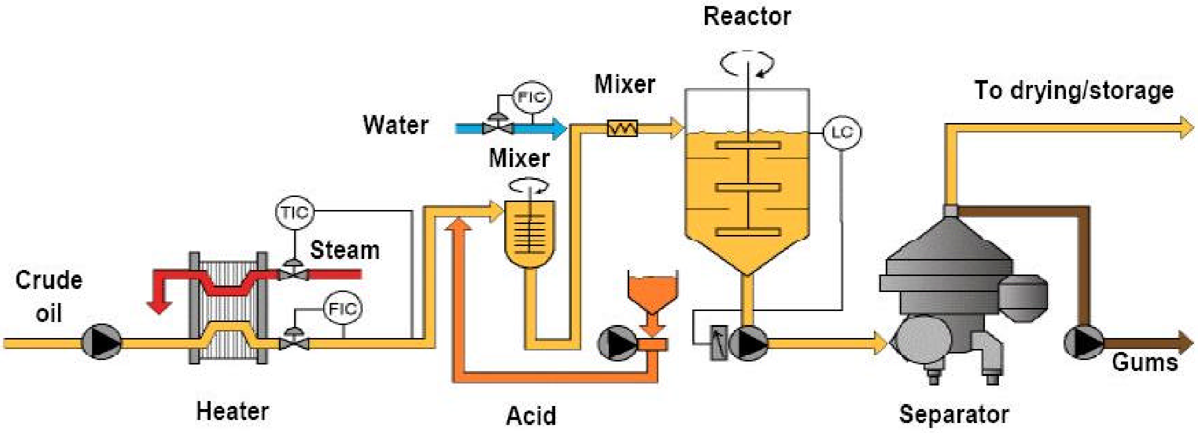


Figure 3-11 Process scheme for acid degumming

3.5.3.6 Acid degumming according to manufacturer DeSmet

DeSmet Ballestra, vegetable oil refinery manufacturer, supplies a.o. wet acid degumming lines. Their claims are:

- More centrifuge maintenance
- Less space requirement
- Higher investment cost
- Better removal efficiency of phosphorus (80-90%)

The process steps for acid degumming are as follows:

- Heating the fat/oil to 80-95°C
- Addition of about 0,1% phosphoric acid, stirring vigorously (highly concentrated phosphoric acid; Silverson mixer)
- Retention vessel 1 (10-20 min.)
- Addition of lye to reach a pH of 5
- Retention vessel 2 (40-50°C) (30-60 min.)
- Remove gums via centrifuge at 70°C
- Mix/wash the oil/fat with 5-10% soft water at 70°C
- Separate the washing water and the clean oil/fat via a washing centrifuge
- Vacuum drying to a water content < 0,1%

Finally DeSmet indicates that the Westfalia or Alfa Laval centrifuges are self cleaning but nevertheless these have to be cleaned on a weekly basis.

3.5.3.7 Super degumming

This process, developed by Segers at Unilever, is a modified acid degumming. The oil is heated to 70 °C and mixed with citric acid. The mixture is allowed to react for 5-15 minutes and subsequently cooled to 25 °C and mixed with water. Then it is transferred to a retention tank where the precipitated gums crystallize. The waiting time can amount up to three hours depending on the hydration rate of the phospholipids.

3.5.3.8 Special Degumming

The special degumming includes a neutralisation step. In this process the oil is heated to 60 °C and vigorously stirred with phosphoric or citric acid. Then concentrated lye is added for neutralisation. Then water is added. The mixture is stirred for 30 minutes and the gums are separated from the oil using a centrifuge. The remaining phosphorus content will be about 15-30 ppm, depending on the type of oil. In Figure 3-11 a process scheme for special degumming is included.

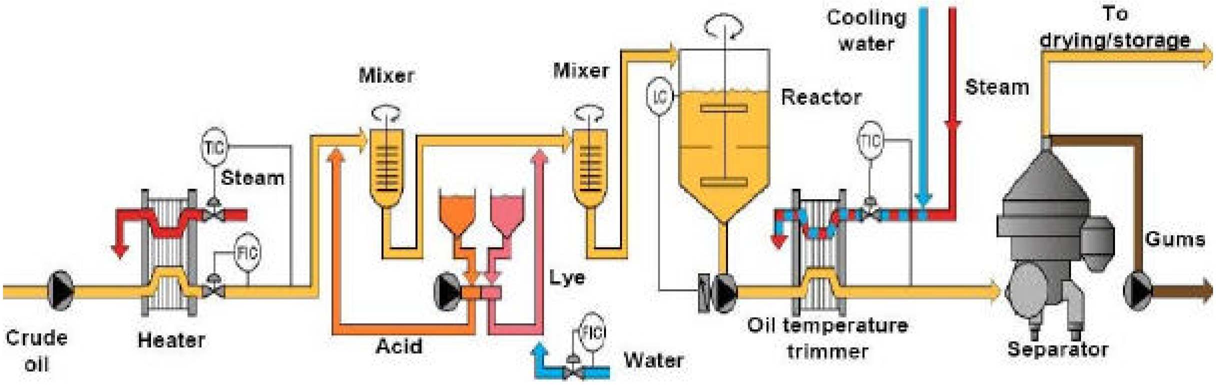


Figure 3-12 Process scheme special degumming

3.5.4 Neutralisation / Chemical refining

At elevated temperatures and in the presence of some water, hydrolysis produces free fatty acids (FFA's). In their free state these are soluble in oil but insoluble in water. This makes it difficult to separate them from the oil. When a sodium hydroxide solution is mixed to raw oil the free fatty acids react to sodium soap. This soap is insoluble in oil and can hence easily be separated in the water phase. Step by step:

- mixing a sodium hydroxide solution with an oil phase to produce soap
- development of the soap phase
- separation of the watery layer from the oil layer

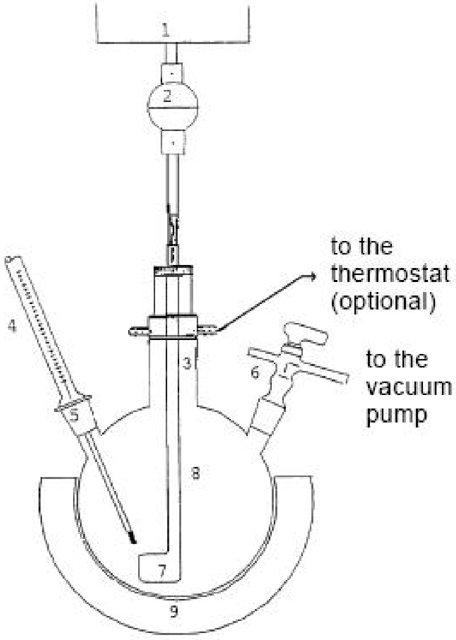
The technique of alkali refining is to find a process with favourable conditions, allowing maximum removal of undesired impurities at a minimum loss of oil.

3.5.5 Bleaching

After physical or chemical treatment the oil undergoes a bleaching step. Originally bleaching was only used to reduce the colour of the oil. The green pigments, coming from chlorofyl, must be completely removed in order to attain a high oxidation stability. But bleaching can be far more powerful. The process also removes undesired side products like metals, traces of soap and phospholipids.
Bleaching can be done with different products, active carbon and bleaching earth. These products show a high absorption capacity because of their high specific surface area. Because of the large number of pores this area can amount to 60 – 300 m^2/g. After the bleaching process the bleaching earth is separated from the oil by filtration.
Bleached oils are highly sensitive to oxidation and hence have to be deodorised within 24 hours after bleaching.

3.5.5.1 Bleaching process

The oil is heated to 100°C under vacuum. Then bleaching earth is added. Its dose is usually between 0,1 – 2,0 mass% but it can, in certain special cases, be as high as 5,0 mass%. The mixture is mixed intensively. It is important that no oxygen may reach the mixture during bleaching. This is realised by processing under vacuum. Then the bleaching earth is separated from the oil by filtering. Figure 3-12 shows a schematic drawing of a lab scale bleaching process.



Vacuum bleaching equipment

1 = Stirrer, infinitely variable (0 - 600 Upm), with tension lining
2 = Flexible coupling
3 = Vacuum stirring plug, grinding NS 29/32
4 = Electronic contact thermometer, range: -50... + 300 °C
5 = Variable conical grinding with contact thermometer, NS 14,5/23
6 = Evacuation attachment with vent hole, NS 14/23
7 = Blade stirrer
8 = Round-bottom three-neck flask, content: 250 ml
medium neck: NS 29/32, side necks: NS 14/23
9 = Heating mantle for 250 ml round bottom flask with carrying grip

Figure 3-13 Bleaching process on a lab scale

Usually a higher dosage of bleaching earth is used for physically refined oils than for chemically refined oils. This is related to the higher amount of phospholipids in physically refined oils. In Figure 3-13 a continuous bleaching process scheme is depicted.

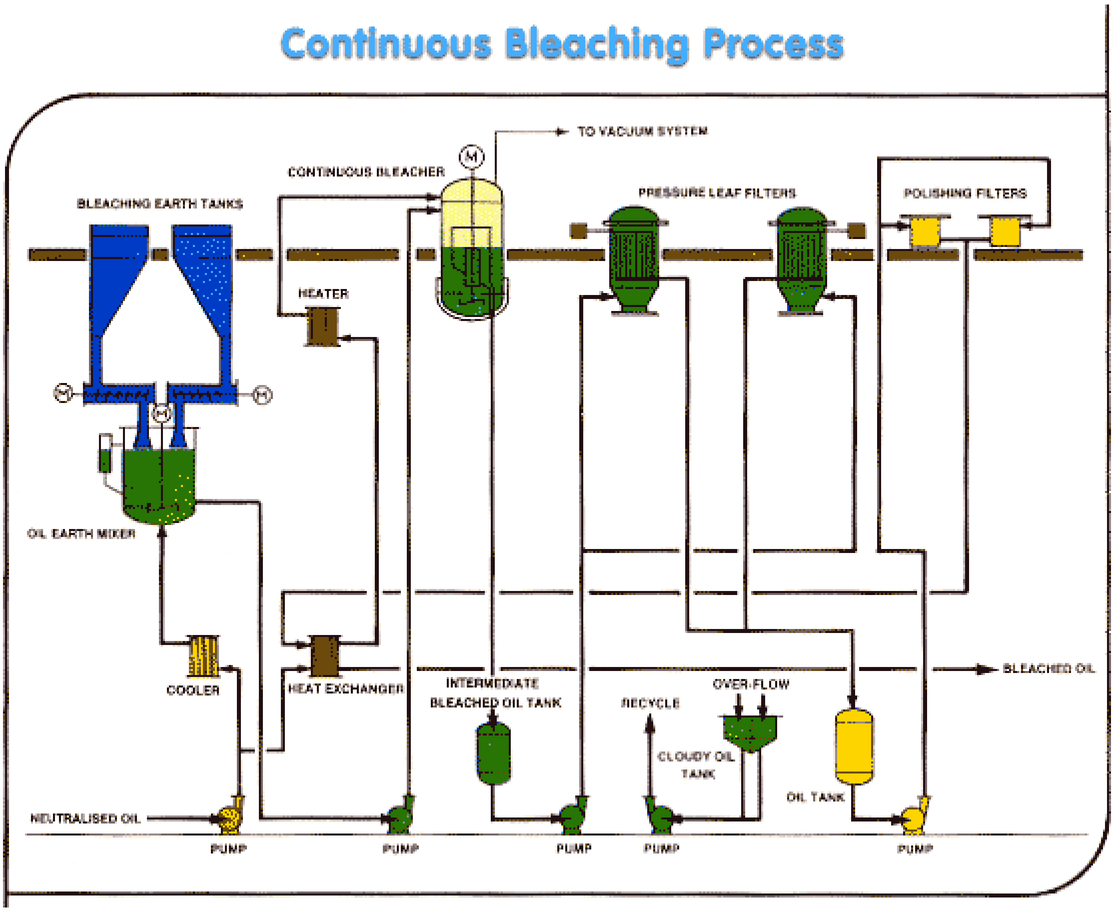


Figure 3-14 Continuous bleaching process [Pennwalt]

3.5.6 Fractional distillation (deodorizing)

Fractional distillation (in literature usually ‘deodorizing’ is used) is the last step in the refining process for oil or fat. The process is based on the large differences in volatility between the oil and undesired substances. In this step the FFA content as well as the content of oxidation products like aldehydes and ketones is remediated. Deodorizing also is the best way to reduce the sulphur content. The process is executed at a temperature of about 260°C and a near-vacuum pressure of 1-3 mbara. The steam flow used normally is about 2% per hour. Input requirements to the oil are <30 ppm of sulphur and <0,1% H_2O.

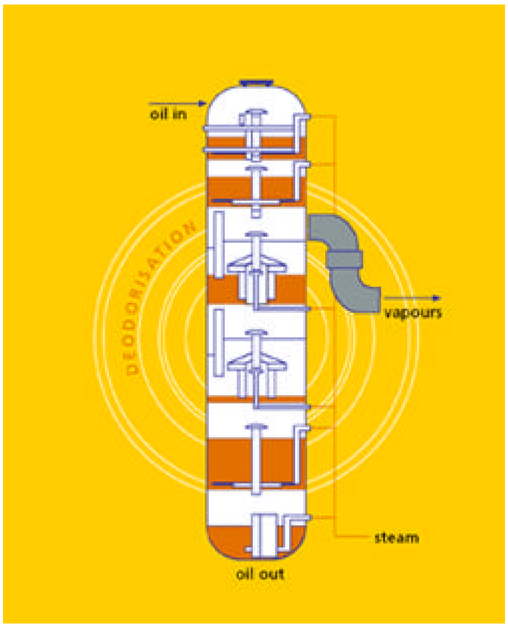


Figure 3-15: Deodorizer (fractional distillation) [AngliaOils]

4 Lessons learnt with bio-oil in stationary diesel engines

This chapter was adapted from [Hoogendoorn, 2006].

4.1 Introduction and incentives

For many years fossil oil (either diesel or residual fuel) was the dominant fuel for power stations based up on stationary Diesel engines. However, due to both the current rise in fossil oil prices since 2002 and the implementation of guaranteed feed-in tariffs for both renewable fuels and combined heat and power (CHP) generation in certain EU countries (notably Germany, Austria) bio-oil CHP is becoming more and more common.

Wärtsilä already started bio-oil engine testing in 1995 while also both MAN B&W and SKL can be described as pioneers. However, some of these early projects have encountered operational problems. Many of these problems find their origin in a lack of fuel quality control, as is mentioned later.

Currently, there are around 50 bio-oil CHP installations larger than 1 MW_e within Western Europe, and new units are being constructed every month. In total, there are currently around 1800 bio-oil CHP units in operation in Germany.

Several incentives are available for the development of a bio-oil fired CHP installation. First, the reduction of CO_2 emission into the atmosphere. Second the possibility to become self-supplying in energy. Third the consideration that buying biofuel from national agriculture has more economic added value than buying fossil fuels abroad.

Unfortunately, due to different renewable electricity policies within the 25 EU member states, a level playing field for bio-oil CHP does still not exist. The lack of a European level field is also true for the application of bio-oil for transportation: the Dutch Tax Administration Agency has already threatened that the continuing use of rapeseed oil in Ingenia’s company van may lead to a maximum of 4 year imprisonment for some of the authors of this report (!).

4.2 Fuel characteristics & Fuel quality demands

The term bio-oil is used for a wide collection of liquid biological fuels. In this article only vegetable oils and animal fat (both unrefined and refined) are discussed.

Ingenia works on a daily basis in the area of fuel quality control and we can conclude that this still is the main bottleneck for reliable bio-oil CHP operation. OEM guarantees and insurances (in case of machine breakdown) are often only valid when stringent fuel quality control takes place.

The most important properties for bio-oil are specified in the table below, together with some guiding values for safe operation.

Table 4-1 Some bio-oil fuel properties for diesel engines with their desired interval for safe operation

Property	**Unit**	**Desired range**
Iodine number	g I_2/100 g	max. 125
Carbon residue	wt%	max. 0,4%
FFA content	wt%	max. 4%
Phosphorus content	mg/kg	max. 15
Ash content	wt%	max. 0,01
Water content	wt%	max. 0,075
Oxidation stability	hours	min. 6 hours

Diesel engines work with a heterogeneous mixture. The intake air is compressed in the cylinder and about top dead centre (TDC) the liquid fuel is injected by the injector nozzle. The temperature of the fuel at this moment approaches 100°C. Upon injection the fuel is atomized into fine droplets that evaporate and consequently burn. For the atomization and combustion of the fuel the viscosity at elevated temperature (~100°C) is of crucial importance. A small viscosity value (i.e. comparable to diesel fuel) will lead to a fast vaporisation and hence a fast, uniform and complete combustion. A large viscosity value will lead to poor atomization and hence slow evaporation of droplets and uneven, or even partial combustion. Both the higher viscosity of bio-oils and their higher distillation end temperature give rise to a slower combustion compared to diesel oil.

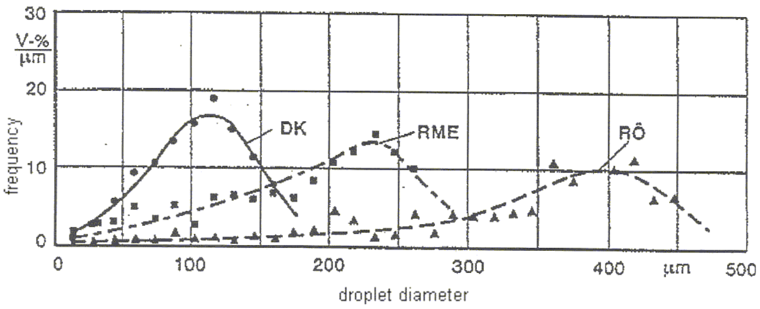


Figure 4-1: Droplet size distribution for diesel fuel (DK), rapeseed methyl ester (RME) and rapeseed oil (RÖ) when atomised at the same pressure and temperature [Tschöke]

4.3 Diesel engine characteristics

Diesel engines can be classified into low-speed (60 – 300 rpm), middle-speed (300 – 1200 rpm) and high-speed engines (1200 – 5000 rpm). It can be concluded that a long residence time in the cylinder is helpful for a complete combustion of the fuel. Hence a lower engine speed is advantageous, giving more time between cycles and hence a longer combustion time. Slow-speed and medium-speed engines are often capable of running on heavy fuel oil, which suffers from the same viscosity problems compared to diesel oil.

Especially direct-injection (DI) diesel engines are sensitive to the fuel's properties. Incomplete combustion may lead to deposits of soot and char on the injector tip, the piston bottom and/or the piston ring area. These deposits are highly undesired and can give rise to increased fuel and/or lube oil consumption, eventually resulting in breakdown of the entire engine.

Ingenia made an inventory of vegetable and animal oils available, and plotted viscosity as a function of temperature for a selection of these oils.

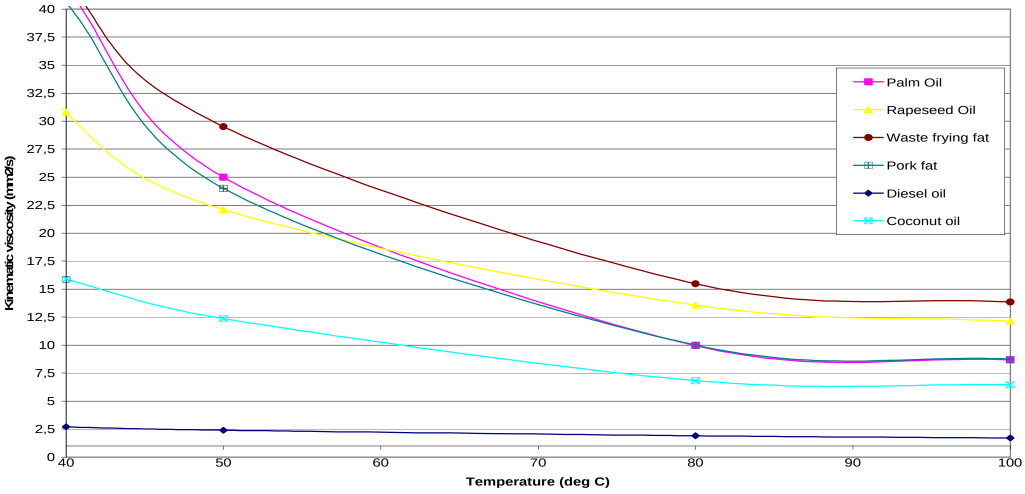


Figure 4-2: Viscosity as a function of temperature for a selection of bio oils and fats

Furthermore a correlation was found between cetane number and iodine number. The iodine number is a measure of the saturation level of the oil. The lower the iodine number, the more saturated fatty acids are present. The higher the iodine number, the more unsaturated fatty acids are present. A low iodine number seems favourable for smooth engine operation.
The cetane number is a way of expressing the ignition and combustion behaviour of a diesel engine fuel. A higher cetane number means a shorter ignition delay of the fuel upon injection, whereas a lower cetane number gives a longer ignition delay, leading to a rough running of the engine and loud diesel knock sound. The figure below shows the correlation that is found, showing that highly saturated bio-oils like animal fat and palm oil have the most favourable ignition properties. As an indicator the European cetane number requirement for road diesel (CN = 51) has been drawn in the graph. Large diesel engines can work with much lower cetane numbers as well.

Furthermore the presence of unsaturated fatty acids in the oil, especially linoleic acid, is known to cause problems, both in polymerization of the fuel in the high-temperature area of injector nozzles and combustion chamber, and in deterioration of the fuel quality during storage.

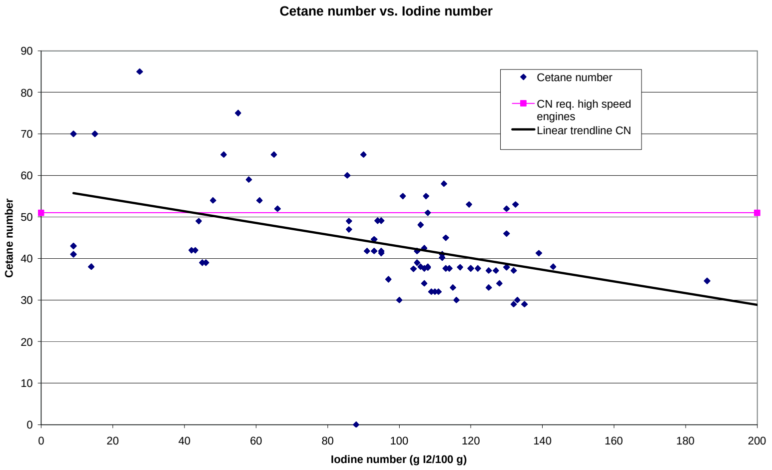


Figure 4-3: Relationship between iodine number and cetane number

Engine adaptations

Depending on the make and type of the engine, modifications are made to the engine for the use of bio-oil. Common modifications of large diesel engines are summarized in table 4-2.

Table 4-2 Common engine adaptations for large diesel engines

Adaptation measure	**Explanation**
More extensive fuel preparation: Fuel heating, filtering and centrifuging, eventually chemical refining	Fuel quality is vital for reliable engine operation. Viscosity, contamination and other parameters must be optimised
Earlier injection timing	Compensation for the longer effective ignition delay of bio-oil
Higher injection pressure	Better atomization of more viscous fuel
Larger oil content of crankcase	Lube oil is more heavily loaded. More oil makes longer oil change interval possible
Decreased maintenance intervals	The engine must be in top condition to ensure trouble-free operation

4.4 Reference projects and engine types

Commonly used engine types are low to medium speed engines by Wärtsilä, MAN B&W, SKL, Cummins, and ABC. In the small range below 100 kWe, Kubota and Yanmar are common engine types. Complete bio-oil CHP installations (mostly turn key) are offered from companies like AEH Power, Kuhse, Tippkötter, GMK and many others. These packagers build their own installations, based on adapted standard OEM diesel engines. Obtaining operational and maintenance guarantees from the OEM for PPO operation is becoming less and less difficult. The use of high quality animal fat is however sometimes only guaranteed by the packaging company and may be without an OEM guarantee. Table 4-3 provides a list of some Western European bio-oil CHP projects (status 2006).

Table 4-3 Recent bio-oil CHP projects in Western Europe

	Capacity	**Engine manufacturer**	**Operator, location**
B	80 (8 x 10 MWe)	MAN B&W	SPE Harelbeke
I	3 x 8 MWe	Wärtsilä	Monopoli
	5 MWe	Wärtsilä	Karlburg
B	10 x 1 MWe	Cummins et al.	Moeskroen
B	4 x 3,2 MWe	ABC	Electrawinds, Oostende
B	1,0 MWe	Cummins	Duffel
D	4 x 2 MWe	ABC	Magdeburg
D	3 x 2 MWe	ABC	Empfingen
D	2,2 MWe	SKL	Sauter
NL	2,1 MWe	MAN B+W	Qlear
A	1,5 MWe	MAN B+W	Qlear (Bregenz)
I	1,5 MWe		Petroplus
A	3 x 1,4 MWe	ABC	Bregenz
I	2 x 1,2 MWe	ABC	Civitella
A	1,0 MWe	MAN B+W	Fritzens
	1 MWe	Deutz	Fernwärme Zwönitz
D	2 x 0,85 MWe	ABC	KWB Rheindürkheim
D	2 x 0,85 MWe	ABC	KWB Sangerhausen
D	1,9 MWe	SKL	Bitterfeld
D	5,33 MWe (3 engines)	SKL	Magdeburg
	3 x 0,8 MWe	MAN	De Becker, Asse
NL	0,65 MWe	ABC	Calluna, Ermelo
	2 x 1,5 MWe	MAN B&W	Eppingen Richen
D	5 MWe	SKL	Biopell, Empfingen

* = partly based upon reference lists by HUG, IPCO and others

4.5 Environment

Generally the emission of CO and unburned components is lower with bio oil compared to fossil oil. As a result of a lack of sulphur in the fuel, the emission of SO_2 from the stack is negligible. Compared to diesel the emission of NO_x from bio oil fired engines is slightly higher. If necessary a $DeNO_x$ installation can be fitted. A properly converted diesel engine running on bio-oil will not lead to an increase in emission of dust (particulate matter, PM) compared to diesel. Nevertheless legislation will demand more and more the use of a dust filter, especially in areas with a high PM concentration in the air, like the Netherlands.

Care must be taken to ensure that the fuel for a bio oil CHP installation is truly sustainable. Recently some discussion arose about the sustainability of palm oil, because there were signals that new large-scale palm oil plantations lead to deforestation of tropical rainforest and banishment of indigenous people. Initiatives like the RSPO (Round Table on Sustainable Palm Oil) were started to control and promote sustainable farming techniques.

4.6 Conclusions

The application of bio-oil CHP is now becoming a proven and reliable technology and is expected to show further market share rises during the coming years. Fuel quality control is still a necessity for reliable operation.

For a sound economic operation of bio-oil CHP installations in different European countries, it will be vital to develop a level playing field for bio-oil CHP. At this moment stimulation regimes vary too much and are too inconsequent in time to allow long-term strategies.

5 Technical feasibility

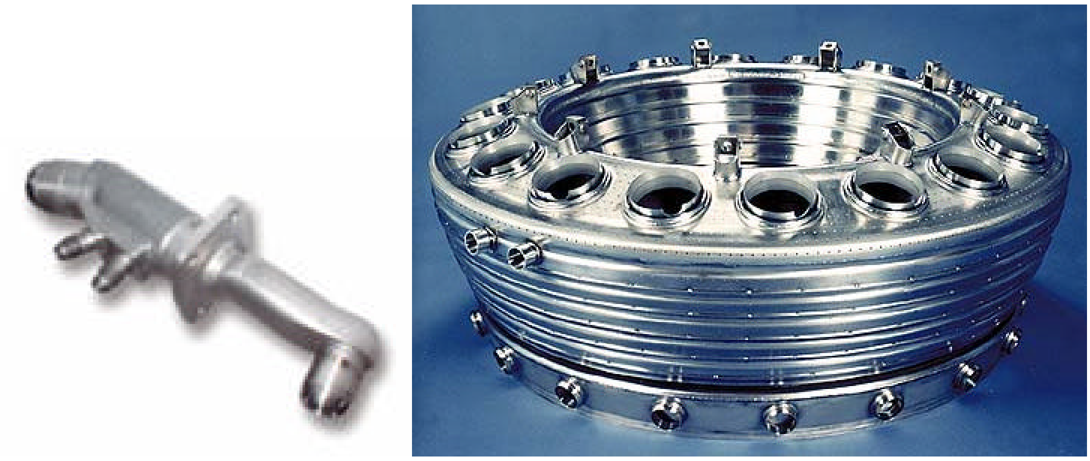
5.1 Combustion chamber geometry

Generally speaking, the combustion chambers can be divided into the following groups:

- Single separate burners (1 or 2 burners);
- Multiple burner systems (“annular can”-type; up to 20 burners)
- Ring shaped combustion chambers with individual burners (figure 5.1)

A combustion process within a gas turbine should comply with the following demands:

- high combustion efficiency (f.i. > 99%) despite low residence times (typically 0,015-0,03 seconds), also in part-load, while having low pressure losses;
- low emission levels (CO, NOx, soot, UHC)
- stable ignition and stable flames without high-energetic damaging vibrations;
- the combustion chamber should be corrosion (and up to a certain level resonance) resistant and should have considerable service life.



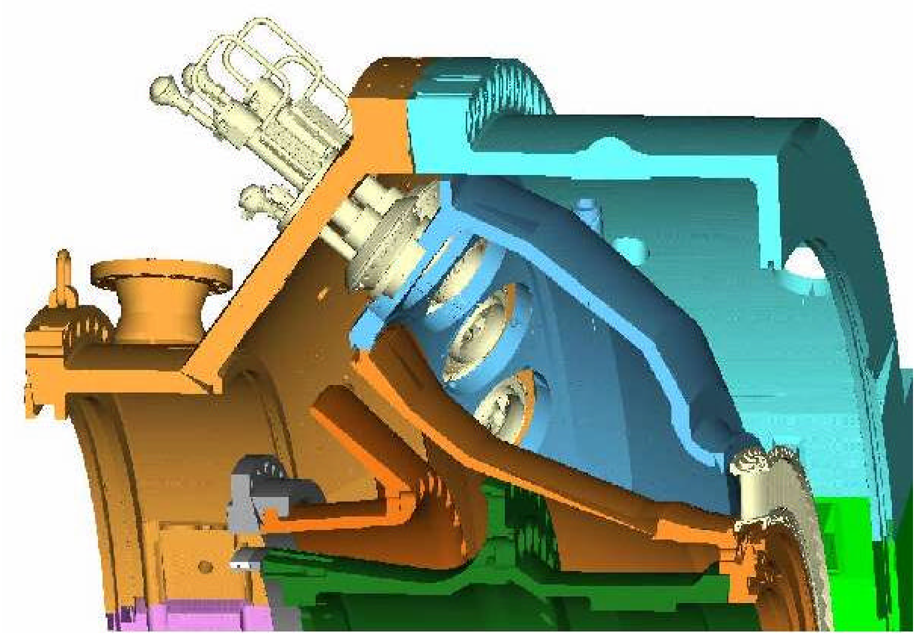


Figure 5-1: Examples of a fuel injector and a ring shaped combustion chambers (Alstom, Siemens)

5.2 Droplet size, ignition and atomisation modelling

As was shown in chapter 4, the application of bio-oil may result in several changes of the ignition, evaporation and combustion process. The liquid fuel is atomized through small orifices (see figure 5-2; Ding-Yuan, 1986) into fine droplets that evaporate and consequently burn.

For the atomization and combustion of the fuel the viscosity at elevated temperature (80-100°C) is of crucial importance. A small viscosity value (i.e. comparable to diesel fuel) will lead to a fast vaporisation and hence a fast, uniform and complete combustion. A large viscosity value will lead to poor atomization and hence slow evaporation of droplets and uneven, or even partial combustion. Both the higher viscosity of bio-oils and their higher distillation end temperature give rise to a slower combustion compared to diesel oil (see also figure 5-3; Rakopoulos, 2006).

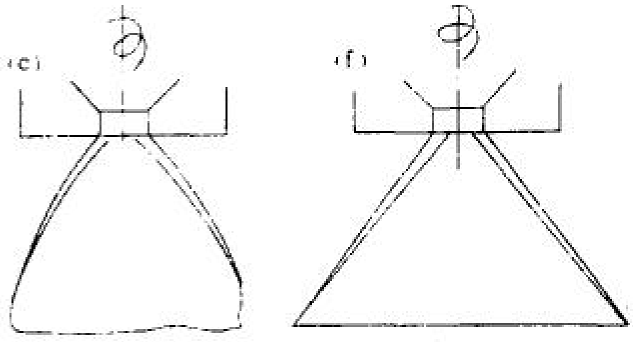


Figure 5-2: Typical shape of an oil spray (where atomization, evaporation and ignition take place)

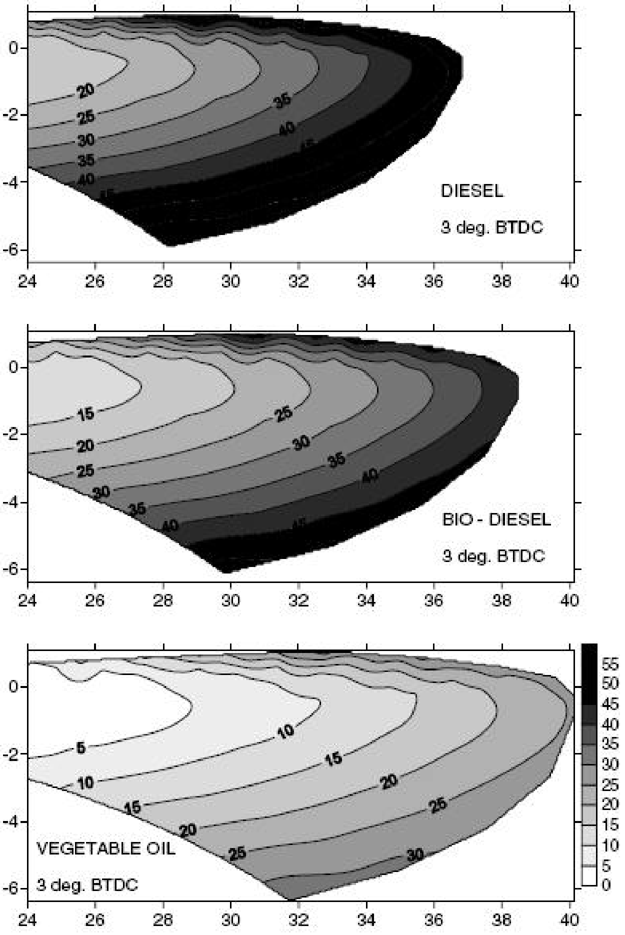
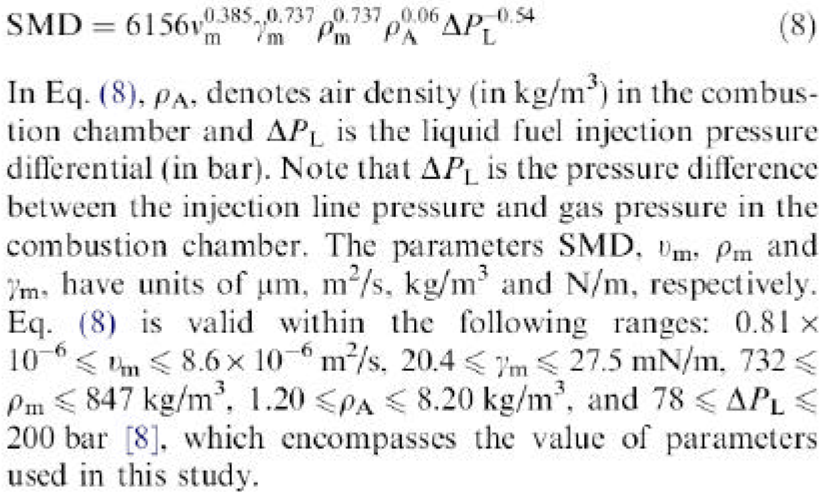


Figure 5-3: Distribution of spray mass fractions of evaporated fuel (as % of total injected fuel)

5.2.1 The Ejim atomisation model

An article by Ejim (2006) proposes a formula which describes the most important factors affecting droplet sizes in spray combustion (figure 5-4) The results from this formula seem, generally, to agree with other information (Rakopoulos, 2006 and Tschöke H. 1995). It was therefore decided to include some plots with a variation of temperature (figure 5.5).



$$\mathrm{SMD} = 6156 \upsilon_{\mathrm{m}}^{0.385} \gamma_{\mathrm{m}}^{0.737} \rho_{\mathrm{m}}^{0.737} \rho_{\mathrm{A}}^{0.06} \Delta P_{\mathrm{L}}^{-0.54} \qquad (8)$$

In Eq. (8), ρ_{A}, denotes air density (in $\mathrm{kg/m^3}$) in the combustion chamber and ΔP_{L} is the liquid fuel injection pressure differential (in bar). Note that ΔP_{L} is the pressure difference between the injection line pressure and gas pressure in the combustion chamber. The parameters SMD, υ_{m}, ρ_{m} and γ_{m}, have units of µm, $\mathrm{m^2/s}$, $\mathrm{kg/m^3}$ and N/m, respectively. Eq. (8) is valid within the following ranges: $0.81 \times 10^{-6} \leqslant \upsilon_{\mathrm{m}} \leqslant 8.6 \times 10^{-6}\ \mathrm{m^2/s}$, $20.4 \leqslant \gamma_{\mathrm{m}} \leqslant 27.5$ mN/m, $732 \leqslant \rho_{\mathrm{m}} \leqslant 847\ \mathrm{kg/m^3}$, $1.20 \leqslant \rho_{\mathrm{A}} \leqslant 8.20\ \mathrm{kg/m^3}$, and $78 \leqslant \Delta P_{\mathrm{L}} \leqslant 200$ bar [8], which encompasses the value of parameters used in this study.

Figure 5-4: Predictive formula for SMD droplet sizes by Ejim et al (2006)

The main input for the Ejim model are viscosities from Figure 2-7 while also surface tension values around 0,035 – 0,04 N/m were taken for bio-oils and 0,023 N/m for the diesel. There is a general lack of public knowledge about the surface tension values for various fuels at different temperatures.

It can be seen that the coconut oil seems to have lowest SMD droplet sizes relative to the other oils. This is caused by the relatively low viscosity of coconut oil when compared to other bio-oils.

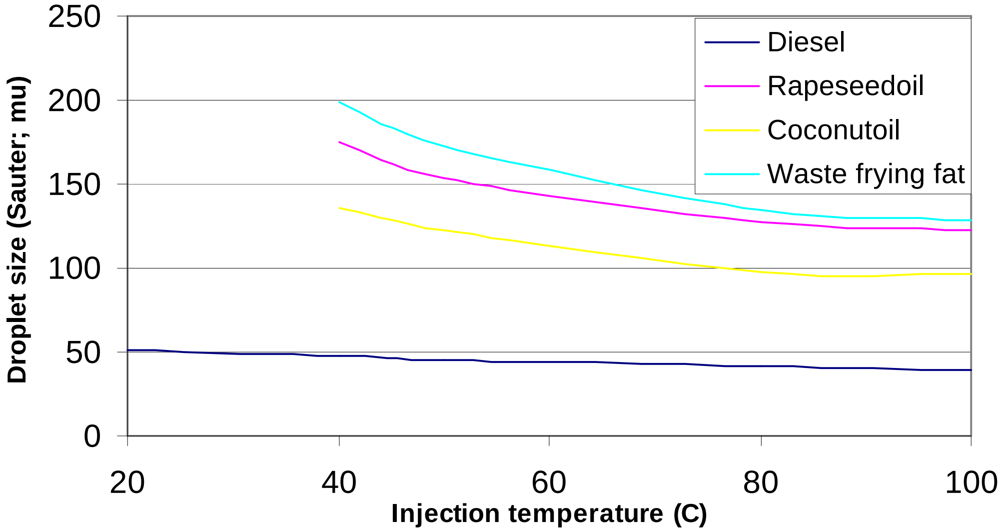


Figure 5-5 Prediction of Sauter mean droplet sizes when applying the formula by Ejim (2006)

5.2.2 TU/e atomisation modelling

The Sauter mean droplet size, as is predicted by the Ejim formula, has got a major impact on both ignition, evaporation and total combustion time needed for sufficient burn out.

The predictions of figure 5-5 clearly show that when injecting a bio fuel, preheating should be implemented to reduce the SMD of the fuel spray droplets. The most efficient preheating temperature seems to be 80°C; above this temperature not much more improvement of the droplet SMD can be obtained. Also considering that at temperatures well above 80°C the bio-fuel could deteriorate chemically or even start boiling, we will study more closely the atomization of an average bio-fuel at 80°C. The atomization characteristics were mainly determined with the following equations that are similar to [Ejim], but also incorporate the nozzle diameter (see Appendix B for the MATLAB-file that was created and used for this analysis). Lin and Reitz (1998) proposed the following condition that will ensure atomisation (break up of the fuel flow after the nozzle into droplets):

$$We_g \geq 40.3$$

With We the Weber-number that is determined by:

$$We = \frac{U^2 r D}{s}$$

Where is U the speed of the fluid leaving the nozzle, r the density of the fluid, D the nozzle hole diameter and s the surface tension. Hiroyasu and Arai (1989) obtained the following empirical relationship for the SMD:

$$\frac{SMD}{D} = 0.38\,\mathrm{Re}^{0.25}\,We_l^{-0.32}\left(\frac{m_l}{m_g}\right)^{0.37}\left(\frac{r_l}{r_g}\right)^{-0.47}$$

Where Re is the Reynolds number, m_l the dynamic viscosity of the fuel, m_g the dynamic viscosity of the combustion air, r_l the density of the liquid and r_g the density of the combustion air.

Figure 5-6 shows minimum required nozzle exit velocity that is necessary to ensure atomisation with varying nozzle diameter, both for diesel and an average bio-oil preheated at 80°C. For the average bio-oil, a density of 925kg/m^3 and a dynamic viscosity of 0.013875 Ns/m^2 are assumed.

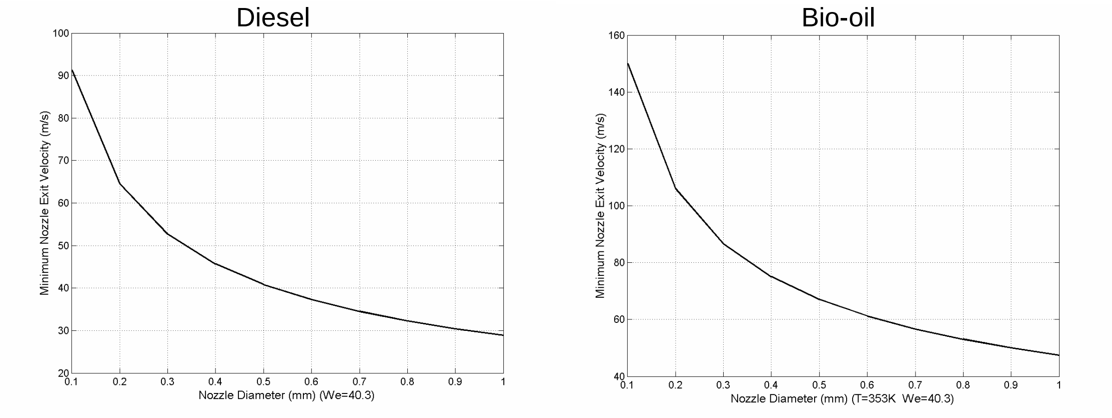


Figure 5-6 Minimum required nozzle exit velocity to ensure atomisation with varying nozzle diameter for diesel and an average bio-oil preheated at 80°C

Note that the lines of figure 5-6 (and also of figure 5-7, 5-8 and 5-9) are in fact constant Weber lines for which $We = 40.3$ is valid[1]. As one would expect, the model shows that the bio-oil spray requires a higher nozzle exit velocity than diesel to ensure atomisation.

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[1] Due to especially surface tension differences between bio-oils and diesel oils, a comparison based up on Weber numbers only may not be adequate.

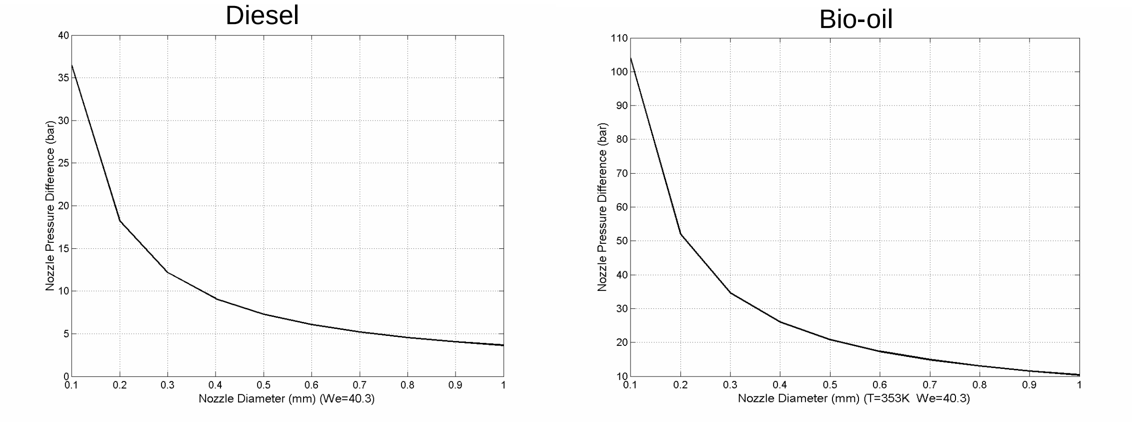


Figure 5-7 Minimum required nozzle pressure to ensure atomisation with varying nozzle diameter for diesel and an average bio-oil preheated at 80°C

The pressures that are needed to obtain the nozzle exit velocities of figure 5-6 are shown in figure 5-7. The bio-fuel needs a considerably higher pressure difference over the nozzle to fulfil the atomisation requirement. On average, the pressure difference over the nozzle for the bio-fuel needs to be 3 times as high as for diesel.

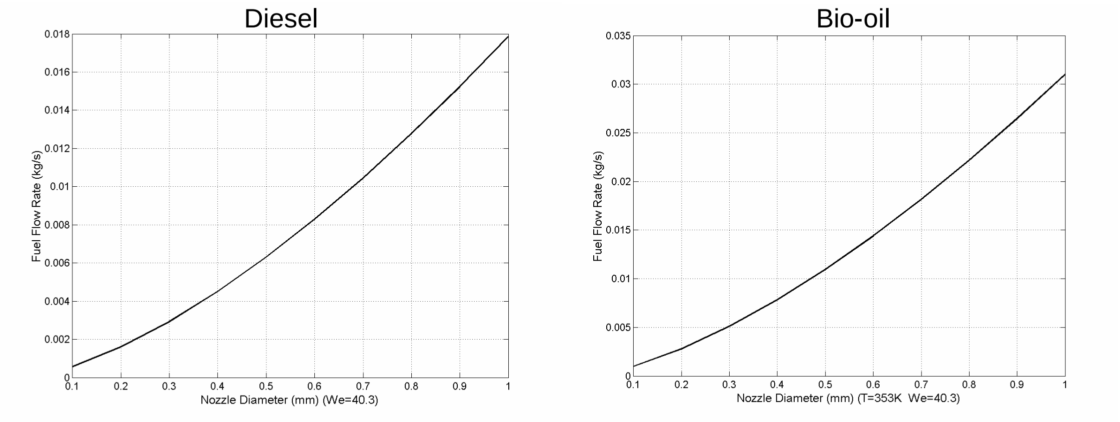


Figure 5-8 Fuel flow at minimum required nozzle exit velocity and nozzle pressure to ensure atomisation with varying nozzle diameter for diesel and an average bio-fuel preheated at 80°C

The corresponding fuel flows to the nozzle pressures of figure 5-7 are shown in figure 5-8.

Finally, in figure 5-9 the resulting SMD of the fuel spray droplets is shown. It can be seen that the SMD of the bio-fuel droplets is typically twice as high (when the bio-fuel is preheated at 80°C) as that of the diesel droplets. This is not exactly the same value as was found with the method of Ejim (figure 5-5), but is however of the same order of magnitude. The differences probably follow from surface tension differences between bio-oils and diesel fuels.

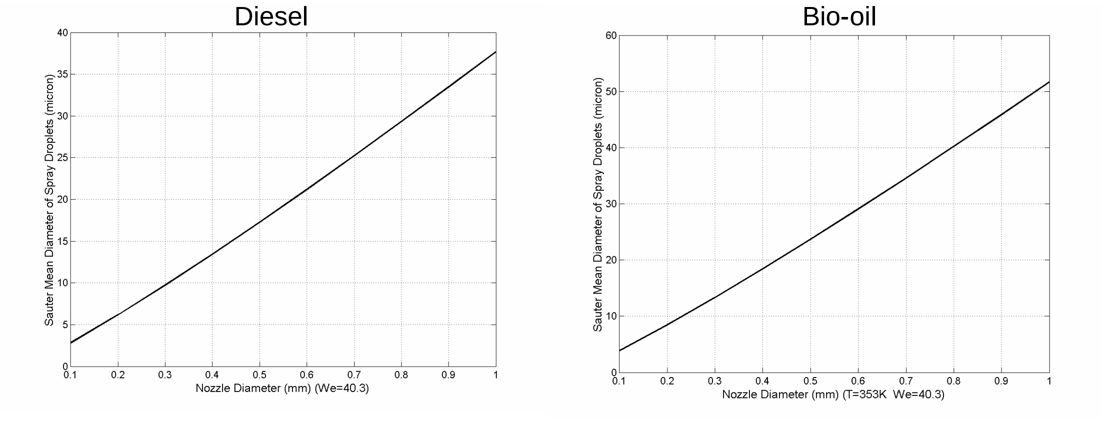


Figure 5-9 SMD of spray droplets at minimum required nozzle exit velocity and nozzle pressure to ensure atomisation with varying nozzle diameter for diesel and an average bio-fuel preheated at 80°C

When making the final design choices it must be realised that every design parameter can only vary within a limited range due to economic and technical considerations. For example, the nozzle pressure is limited by the availability of a fuel pump that can realize this pressure for competitive investment costs. Fortunately the results of figure 5-5 to 5-9 offer an achievable region of parameters that satisfy atomisation, fuel flow rate and spray droplet size requirements. Also when designing a bio-fuel injection system, the SMD could be reduced further by increasing the nozzle pressure as high as possible. However, with bio-fuel it will be virtually impossible to achieve the same SMD as with diesel (and diesel-like fuels); the SMD of bio-fuel droplets will always be a bit higher, even with preheating and increasing nozzle pressure.

Thus, the implications may well be that under certain conditions the starting of an engine could better be executed with diesel (until the combustion chamber is hot and good evaporation and ignition takes place) while also low load ignition and low load combustion behaviour may be more difficult when using bio-oils. The time needed for evaporation and combustion of droplets of equal composition can be estimated while applying the so called R^2-law. This means that bio-oil droplets, that may have a 2-3 times bigger radius, may burn 4 (= 2 * 2) to 9 times slower than diesel droplets (only regarding droplet size). A four to nine times slower combustion process may easily lead to a too low combustion efficiency and too high soot, CO and UHC / C_xH_y-emissions. This is where total residence times inside the hot combustion chamber become important (typically only 0,015 to 0,03 seconds).

5.2.3 Slagging, fouling, corrosion

Compressor fouling may be caused by:

- Salt and dust in ambient air
- Oil vapours from gas turbine leakage

Compressor fouling may result in a loss of around 5% of maximum electrical power after which the gas turbine should be cleaned. It is also possible that constituents within the oil and/or improper combustion may result in fouling or slagging inside the hot sections of the gas turbine.

Cleaning of a gas turbine may be executed in either a dry way (nuts, hulls, rice) or with water and cleaning agents. For the wet cleaning the gas turbine unit has to be at lower speed (RPM) and cooled down.

For the hot path the following can be said. Vanadium pentoxide melts at 680°C. Eutectics formed from combinations of sodium, potassium and calcium with vanadium, lead and sulphur have lower melting points ranging into the 500-600°C range. Deposits resulting from this ash foul the power section blades and vanes and are catastrophically corrosive above their melting points. The problem is controlled by eliminating and modifying the ash to higher melting species which do not adhere to hot path parts.

Oxidation and hot corrosion within the hot sections of a gas turbine may take place in the combustion chamber (f.i. due to flame impingement) and at the expansion stages of the gas turbine or HRSG.

Figure 5-10 Damage of turbine guide vanes due to combustion problems (www.gpal.co.uk)

The potentially most harmful phases during the work-cycles of the turbine are start-up and power-transients. During start-up the expansion turbine housing and blades are cold, which makes them vulnerable to condensing contaminants. The transient power phases are potentially harmful while the combustion chambers are liable to produce soot-particles (especially during power-increase).

For the non-cooled radial turbine in the RCG, the risks of these transient-contaminating phases is limited. The condensed particles will be removed during stable operation, while the soot may cause a thin layer on the blades (similar to the known soot-scale in Diesel turbo-chargers). The effect of the latter is a gradual decrease of the available through-flow surface which can be easily monitored.
For film-cooled gas turbines the effect of the contaminants is potentially more hazardous. During the start-up of the turbine the blades and housing are cold, therefore, the film cooling holes (with typically sub-millimeter diameter) can be easily blocked. If this blockage is restricted to an outer layer it will most likely also disappear during steady operation. However, if the cooling holes are blocked more severely the 'evaporating' phase may take to long. An additional problem to this is that the cooling air out of the film cooling holes will lead to local condensing even during steady operation. Especially, the nozzle leading edges will suffer from this, since the separation vortex at the leading edge leads to an

inward directed flow. This will cause a growing condense bubble which eventually may cause nozzle blockage. The size of the leading edge vortex is in the order of 0.1 mm, which means that particles in the 10 micron range will follow this flow. Therefore, the leading edge bubble will fill not only with condensing contaminants but also with any particulates (including soot).
Summarizing, the effect of contaminated gasses in a non-cooled radial turbine are negligible. On the other hand, for a film-cooled axial turbine problems with clogging of the nozzles are highly probable and application of these turbines to bio-oil combustion will be restricted to very clean combustion exhausts.

In the waste heat boiler, due to fouling, the thermal resistance will rise and the steam production will diminish. According to [Senior], as the fouling layer thickness increases with time, its thermal resistance increases too, which results in an increase in the surface temperature of the fouling layer. If the surface temperature of the fouling layer becomes higher than a certain limit, which is known as the minimum sintering temperature, sintering takes place. The minimum sintering temperature is usually far below the melting point of the fouling layer material. Sintering leads to the reduction of the void volume and reinforcement of the contact bridges between the particles of the fouling layer [Ristic] and is therefore responsible for strengthening of the fouling layer as has been measured by [Skrifvars et al]. The reduction in porosity during sintering also results in increased thermal conductivity as was observed by [Rezaei et al.] for coal ashes and synthetic ash samples. The fouling rate is determined by the difference between the deposition and removal of particles on and from the fouling layer, [Kern and Seaton]. [Abd-Elhady et al.] found that sintering reduces the fouling rate of heat exchangers by lowering the deposition of new particles and increasing the removal rate of newly deposited particles.

Removal of particles from sintered fouling layers during operation of heat exchangers can happen either due to a shear flow, as studied by [Cabrejos and Klinzing] and [Al-Hayes and Winterton], or due to an incident particle impact as shown by [Werner and Haff]. [Müller-Steinhagen et al.] and [Grillot and Icart] have shown that when the gas speed is increased particulate fouling is reduced. For powdery fouling layers, particulate fouling can be avoided when the gas speed is above the critical flow velocity, [Abd-Elhady et al]. However, due to sintering, the fouling layer hardens in time and can become strong enough such that removal of particles by shear flow becomes ineffective, as found by

[Frederick et al.], [Barnhart and Williams] and [Senior]. The cleaning of a heat recovery steam generator (HRSG) may also be performed with soot blowers which use steam or compressed air.

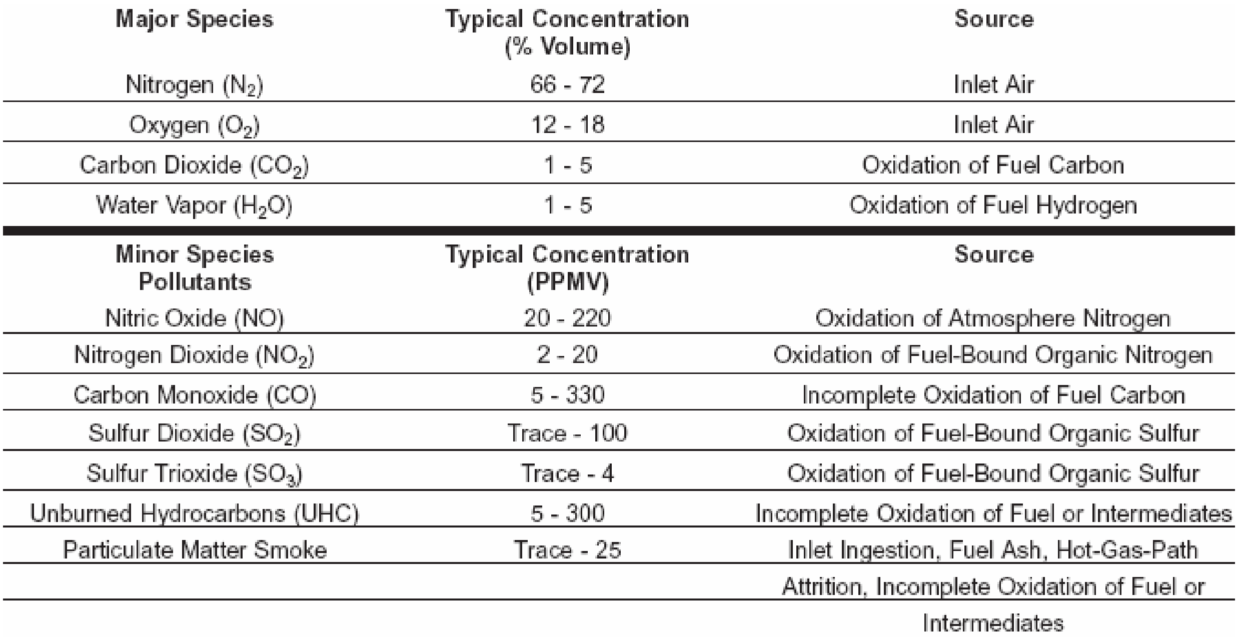
Models have been proposed to characterize the deposition process. They incorporate formation, boiler aerodynamics, transport regimes and sticking of the particles to the deposition surface. A first approach to develop a model for on-line detection of S&F has been started in the SLAGMOD project, where a model based on the data of the steam cycle detect the change of heat transfer. It is an indirect approach for slagging detection. However it cannot provide all the information since the slag formation itself is not monitored. Results from previous and ongoing activities described before, as well as experience from the operation of biomass fired boiler, clearly show a research demand towards methods for on line detection and prevention of S&F in large-scale boilers. On-line information about the deposits being formed in the boiler is of utmost importance to the operators for the application of operational changes, cleaning procedures, and use of different fuel qualities ensuring low risk of slagging, fouling or corrosion phenomena.

5.2.4 Emissions

<u>Flue gas emissions when firing natural gas</u>

Most of the existing gas turbines are using natural gas as input and modern gas turbines can achieve very low NO_x emission levels of f.i. 20-220 ppm on 12-18 vol% oxygen, wet (see table below).

Table 5-1 Typical emission levels burning conventional fuels (GE Power)



Major Species	Typical Concentration (% Volume)	Source
Nitrogen (N_2)	66 - 72	Inlet Air
Oxygen (O_2)	12 - 18	Inlet Air
Carbon Dioxide (CO_2)	1 - 5	Oxidation of Fuel Carbon
Water Vapor (H_2O)	1 - 5	Oxidation of Fuel Hydrogen
Minor Species Pollutants	**Typical Concentration (PPMV)**	**Source**
Nitric Oxide (NO)	20 - 220	Oxidation of Atmosphere Nitrogen
Nitrogen Dioxide (NO_2)	2 - 20	Oxidation of Fuel-Bound Organic Nitrogen
Carbon Monoxide (CO)	5 - 330	Incomplete Oxidation of Fuel Carbon
Sulfur Dioxide (SO_2)	Trace - 100	Oxidation of Fuel-Bound Organic Sulfur
Sulfur Trioxide (SO_3)	Trace - 4	Oxidation of Fuel-Bound Organic Sulfur
Unburned Hydrocarbons (UHC)	5 - 300	Incomplete Oxidation of Fuel or Intermediates
Particulate Matter Smoke	Trace - 25	Inlet Ingestion, Fuel Ash, Hot-Gas-Path Attrition, Incomplete Oxidation of Fuel or Intermediates

When using natural gas, thermal NO_x is the dominant NO_x formation route and thus, NO_x is mainly depending on adiabatic flame temperature (see figure below) and combustor design. The adiabatic flame temperature in an existing combustor is a function of natural gas composition, heat rate (MW_{th}), fuel-air ratio. Figure 5-11 also shows the typical adverse trends of NO_x (going up) and CO (going down). When the CO emission levels go up at lower adiabatic flame temperatures and/or part load operation, it often coincides with a lower combustion efficiency and higher VOC and UHC levels.

Flue gas emissions when firing fossil oil and bio-oils

When firing oils, the NO_x levels are typically higher because of the additional impact of fuel NO_x (see figure 5-12). Depending on fuel type and combustor design, a fraction of 5-20% of the fuel bound nitrogen may typically be converted towards NO_x and thus fuel NO_x becomes the dominant NO_x route. In order to achieve complete combustion sufficient residence time and sufficient atomisation are required (see previous chapter). Insufficient or unstable combustion will result in combustor damage, elevated soot and/or unburnt hydrocarbon (UHC) levels.

Soot and smoke emissions may often correlate with changes in the fuel composition: high Conradson Carbon residue fuel tests and higher aromatic and/or polymer levels within the fuel.

Bio-oils typically have very low sulphur contents (below 100 ppm) and this will results in very low SO_2 emissions when compared to fossil fuel oils.

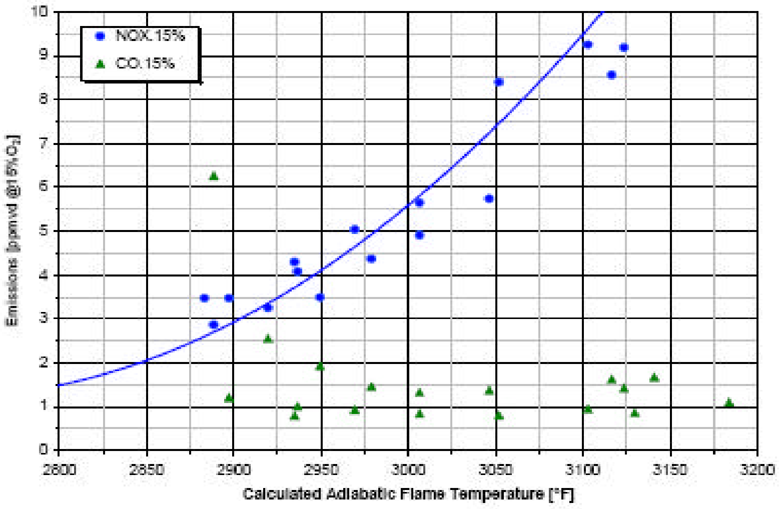


Figure 5-11 NO_x and CO emissions versus adiabatic flame temperature for natural gas [Greenberg].

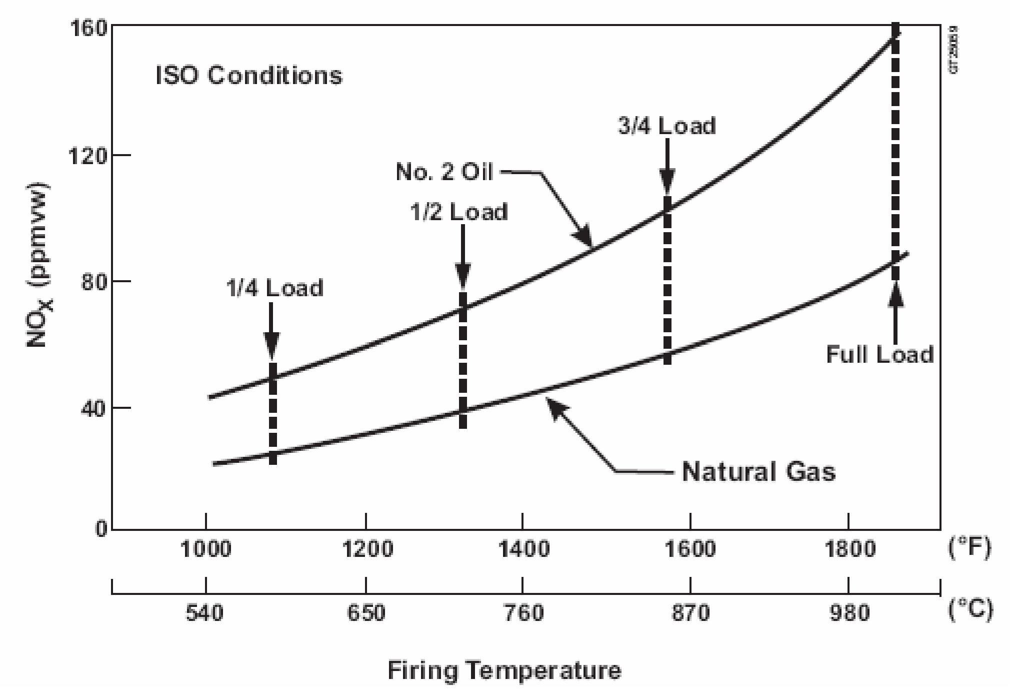


Figure 5-12 NO$_x$ emission levels burning No. 2 Oil and natural gas in a GE MS5001 gas turbine

5.2.5 Fuel line design

As was shown in chapter 3, fuel quality control and fuel preparation is essential in order to obtain reliable operation. Section 5.1 showed that when operating at bio fuel, preheating of the fuel is essential. Conventional configurations could probably adapted for operation on various liquid bio fuels when a fuel line with 1st stage preheating, filter, high pressure fuel pump and 2nd stage preheating (see figure 5-13) is implemented.

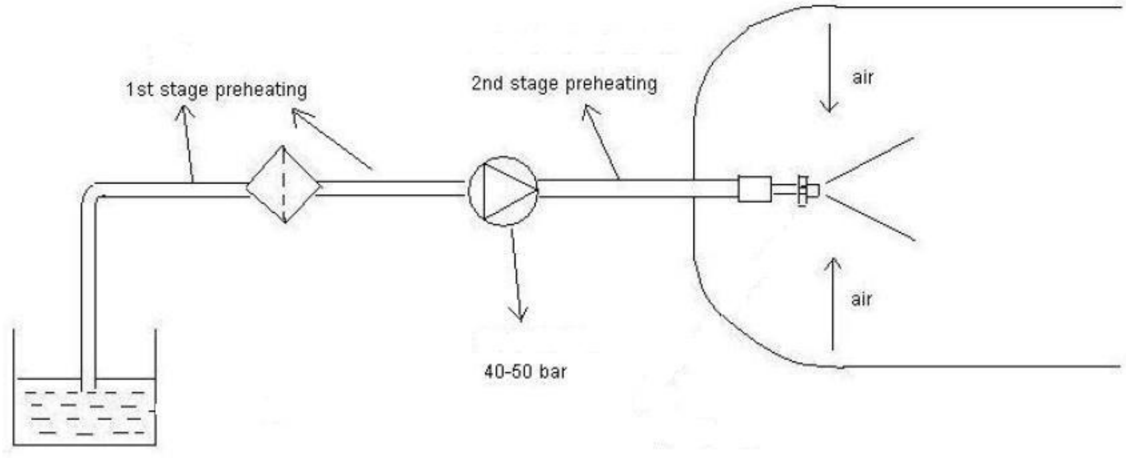


Figure 5-13 Schematic of a bio-oil fuel line

Also it is preferable to design the fuel line in such a way that the nozzle pressure is as high as possible, the current maximum of displacement pumps (which are price competitive) is about 40-50 bar. Figure 5-14 shows an example of a displacement pump.

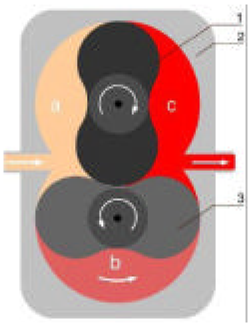


Figure 5-14 Example of a positive displacement pump

5.2.6 Combustion chamber

Section 5.1 showed that with proper design of the fuel line, the SMD of the bio-fuel droplets can be made as small as possible but will always remain larger than for diesel-like fossil fuels. Therefore, it can be advantageous to prolong the residence time to ensure complete and clean combustion. The combustion chamber design should feature internal (recuperative) cooling (and thus preheating of the combustion air) and should be longer (and/or have more volume) than the conventional combustion chamber to ensure a long enough residence time for combustion of the bio-oil droplets (see figure 5-15).

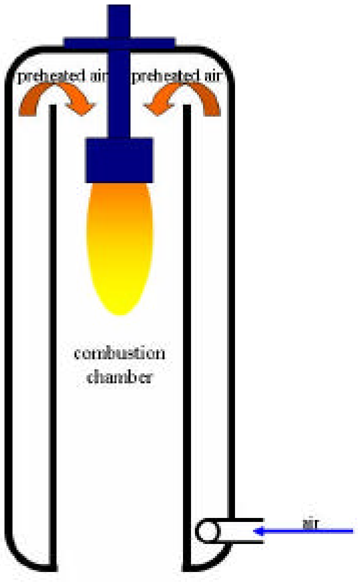


Figure 5-15 Example of a long combustion chamber with internal cooling and preheating of the combustion air

Also the gas turbine layout should be suitable for the existing combustion chamber to be replaced by a much longer or larger version. Typically, this will be possible with industrial gas turbines, but in general will be difficult for aero derivative gas turbines.

5.2.7 Turbines

Expansion turbines can be of the radial or the axial type. Radial turbines are suitable for relatively low mass flows while axial turbines are most fit for higher mass flows. Therefore radial turbines are implemented in the shaft power range 30kW (micro turbine) up to 1MW and for gas turbines with a shaft power > 1MW, usually an axial turbine is the turbine of choice. Radial turbines are rigid and have low investment costs. They will handle soot and other pollution in the hot gasses they expand very well, as they have done for decades in turbocharger applications. It is therefore expected that gas turbines with radial turbines do not need adjustments for their expansion turbine component to be able to operate on even crude bio-fuels. Axial turbines however can be more vulnerable, since their construction is less robust. Specifically an axial turbine with cooled blades will encounter trouble when operated with a gas stream with soot and ash particles; the cooling holes will get clogged, and overheating will result in severe damage of the turbine. It is therefore very doubtful that they can be operated with crude bio fuels. The uncooled axial turbine however, could be operated on crude bio fuels with the inherent exhaust gas stream with soot and particles, if the maintenance and/or cleaning interval are adjusted accordingly.

5.2.8 Waste heat boiler

Since the exhaust gas stream might contain particles that will stick to the tubes of the steam generator when operating on crude bio-fuels, the casing of the boiler or steam generator should be designed in such a way that the tubes can be easily accessed for cleaning. For large steam generators of energy plants there is already extensive experience with fouling control and periodic cleaning. However smaller industrial size steam generators are typically only run on natural gas or oil. This means that they will be able to handle operation on refined bio fuels, but if they are to be operated on crude bio fuels it should be possible to catch particles and ashes before they enter the steam generator. Analogous to section 5.3.5 this could be done by adding an exhaust gas soot collector that separates particles and ashes from the exhaust gas stream before it is supplied to the steam generator by decreasing the velocity of the exhaust gas stream, impaction separation or with (hot) cyclone technology.

5.3 Rankine Compression Gas turbines (RCG)

5.3.1 Fuel

The Rankine Compression Gas turbine (RCG) is a new type of combined cycle and was introduced in section 1.3.2. Because the development of the RCG started at the beginning of the 21st century, Eindhoven Technical University and the company Heat Power aimed at designing the RCG in such a way that it will be capable of burning almost all types of liquid biofuel. When the Dutch government stopped giving new permits for the production of electricity with “MEP-subsidie” (a funding program for production of renewable electricity) in 2006, it was no longer feasible to realize new decentralized bio-fueled combined heat power plants in the Netherlands. However, the RCG was already made suitable for oils and Heat Power wanted to launch the RCG in the Netherlands. Now Heat Power is developing a demo RCG combined heat and power plant that runs on crude glycerin, the by-product of bio-diesel production, which can be economically appealing even without government support. From a technological point of view glycerin is a very challenging bio fuel; it has a low calorific value and a high viscosity (617mm^2/s@ 23°C). Also, the most economically attractive form, glycerine with alkaline and ashes, is even more challenging. It is believed that once the RCG is suitable for crude glycerin, it is suitable for any liquid bio fuel. Therefore the RCG will be the only small gas turbine system (1-10MW range) that will be capable of running on crude biofuels.

5.3.2 Fuel line design

Figure 5-16 shows a cross-section of a straight channel fuel nozzle. This type of nozzle was selected for the RCG-prototype and it will also be implemented in the first real-scale RCG in 2008. For the prototype a nozzle hole diameter of 0.4 mm was selected. In the following the fuel flow and atomization characteristics when glycerin is injected with this nozzle are treated.

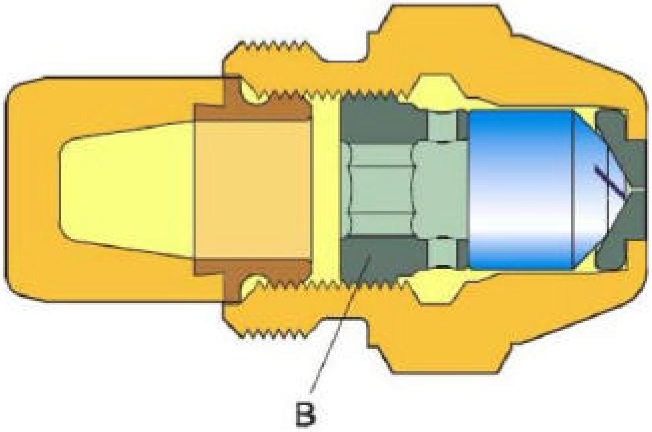


Figure 5-16 Cross-section of a straight channel fuel nozzle

In figure 5-17 the correlation between nozzle pressure, Sauter Mean Diameter (SMD) of the fuel spray droplets and the fuel flow is shown. From figure 5-17 it follows that increasing the nozzle pressure results in a lower SMD and of course a higher fuel flow.

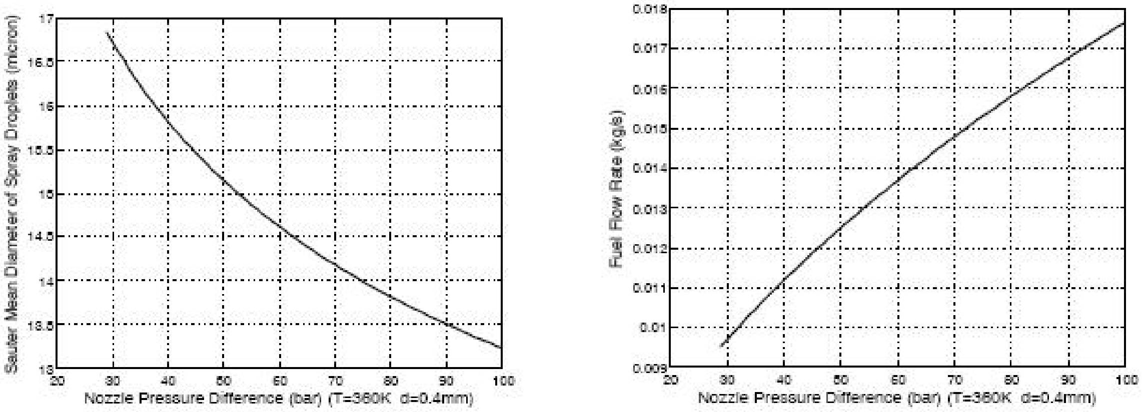


Figure 5-17 left: SMD versus nozzle pressure; right: fuel flow versus pressure

In figure 5-18 it can be seen that increasing the temperature of the fuel with preheating results in a decrease of the SMD but also in a small decrease of the fuel flow.

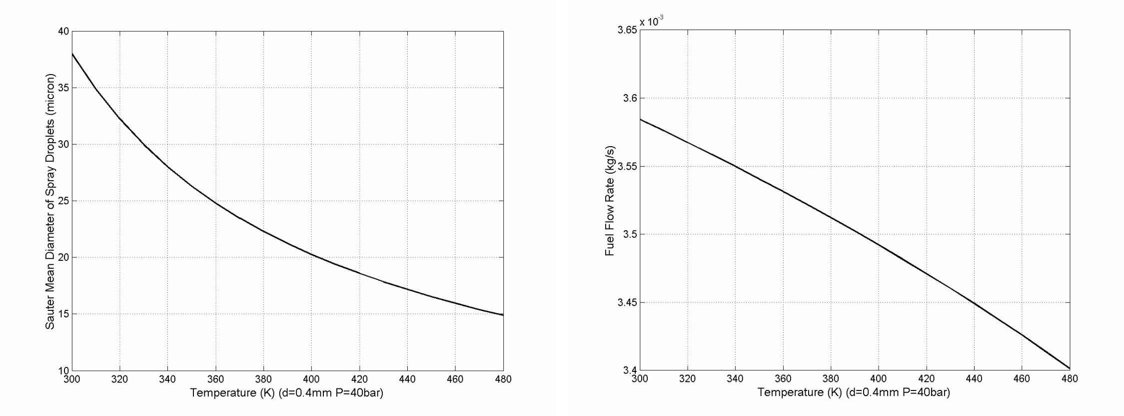


Figure 5-18 left: SMD versus fuel temperature; right: fuel flow versus temperature

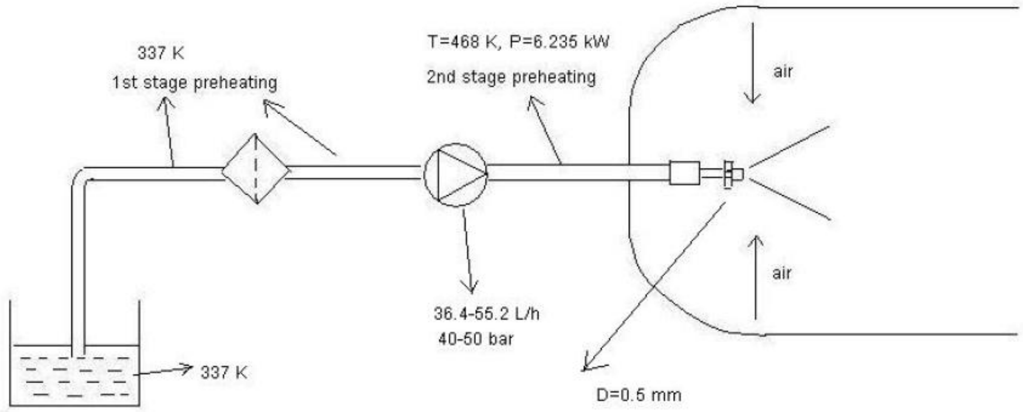


Figure 5-19 schematic of the RCG fuel line

A schematic of the RCG fuel line is shown in figure 5-19, from left to right: fuel tank, 1st stage preheating, filter, fuel pump, 2nd stage preheating and fuel nozzle in the combustion chamber. Preheating is an important measure to guarantee easy pumping and good atomization of the fuel spray when it is injected in the combustion chamber. Crude glycerin contains water and methanol. Water of course boils at 100°C and methanol has its boiling point at around 65°C. Even if the water and methanol mass percentage would be very low, the volume occupied by their vapour would still be considerable because of the liquid-to-gas phase change. To prevent cavitations in the fuel pump and interrupted fuel flow through the nozzle, a two stage preheating arrangement is implemented. The first heating stage should not exceed 65°C. The second heating stage can go up to 195°C because it is after the fuel pump which pressurizes the fuel from 1 to 40 bar. However, for crude bio-fuels in general the temperature of 195°C might be to high and cause deterioration, therefore the preheating temperature will be lowered when running on crude bio-fuels. To be able to achieve the pressure ratio of 40 a positive displacement pump is the most suitable choice (figure 5-14).

5.3.3 Combustion chamber

Since the RCG operates at the relatively low pressure ratio of 3 up to 4 (see section 1.3.3), it cannot make use of existing combustion chambers of conventional gas turbines, which are all operating at much higher pressure ratios. Therefore a combustion chamber was developed especially for the RCG, and the result is a cross-over of a duct-burner and an industrial gas turbine combustor with internal cooling (see figure 5-15).

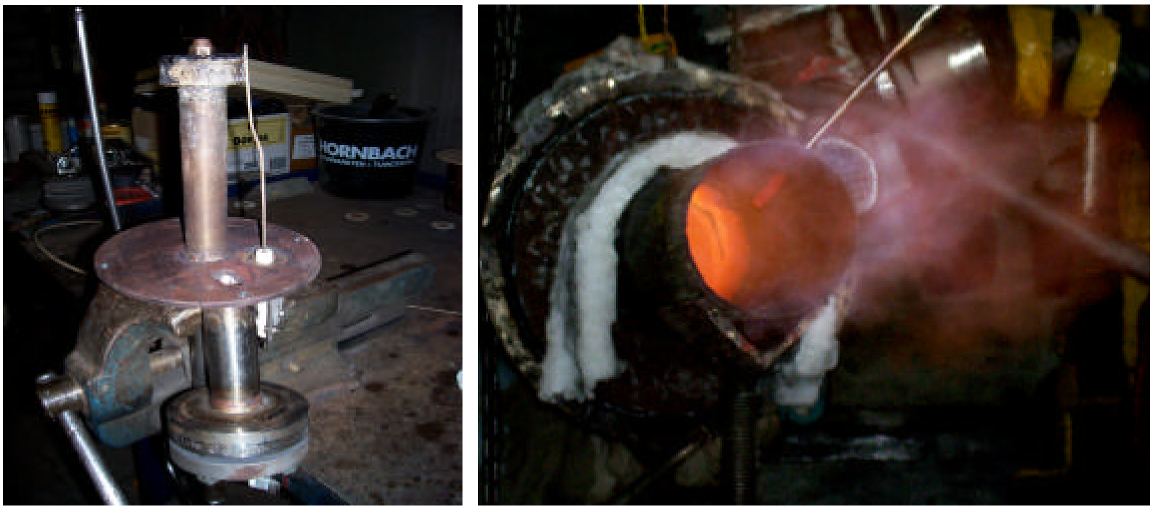


Figure 5-20 Left: picture of the dual-fuel natural gas and glycerin injector after operation
Right: experiments of the RCG crude bio-fuel combustor running on crude glycerin

The RCG combustor has internal (recuperative) cooling for low-NO_x combustion and has a long afterburner chamber to ensure a long enough residence time for combustion of the bio-oil droplets. In figure 5-20 right a picture is shown of experiments with the RCG combustor running on glycerin. The experiments show that the combustor has a NOx-emission of 52 ppm and zero ppm CO-emission. With these emission values this crude bio-fuel combustor fulfils present and future (2010) NO_x- and

CO-emission requirements. The experiments also show that the alkaline is present in the exhaust gas stream in the form of small droplets of alkaline salts. The possible change of the chemical composition of the alkaline salts during the combustion process was studied with a model by the section combustion technology from Eindhoven University. The model predicted that alkalines (potassium hydroxide and potassium soaps) will react into potassium carbonate (K_2CO_3). This was checked with laboratory tests on the available samples from the combustor experiments, and proved to be right: all the alkalines react into potassium carbonate (see fig. 5-21 left hand side, and compare with 5-20, right hand side).

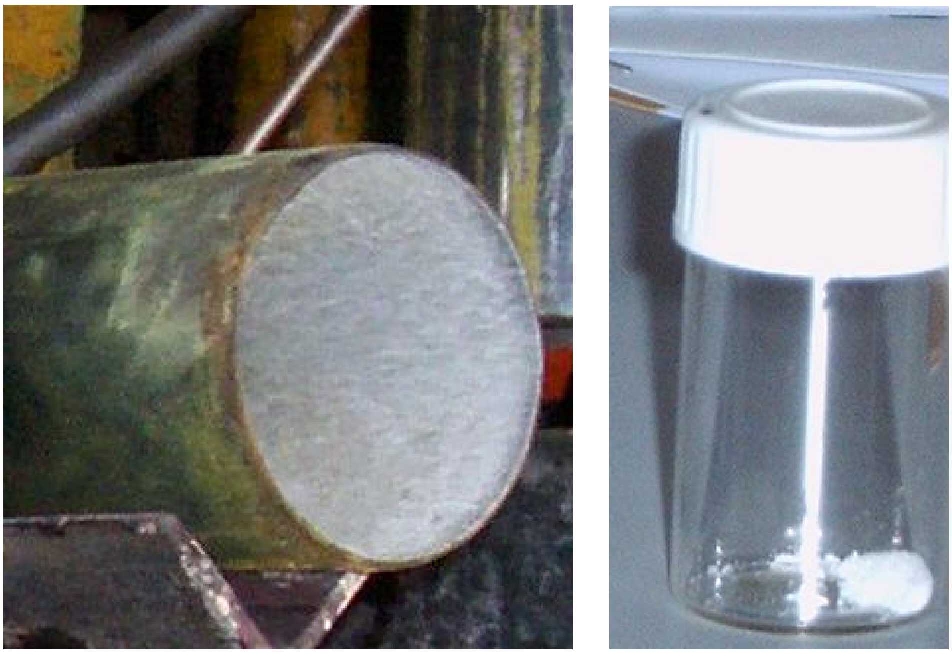


Figure 5-21 Left: potassium carbonate deposit on the cold combustor outlet
Right: collected potassium carbonate from combustor outlet

5.3.4 Turbines

When considering the turbine of the RCG the same applies as for the combustion chamber; it runs on a pressure ratio of 3 up to 4 which is again much lower then that of conventional gas turbines. Therefore, existing turbines of conventional gas turbines cannot be applied in the RCG. Other options were considered, keeping in mind that dual-fuel operation on natural gas and bio-fuels should be possible and that the strategy was that rotating turbo components such as the compressor, turbine and steam turbine should never be developed especially for the RCG, but should be existing technology. Finally it was chosen to employ the radial turbine of a turbocharger that is normally fitted on a stoichiometric industrial gas engine (see figure 5-22).

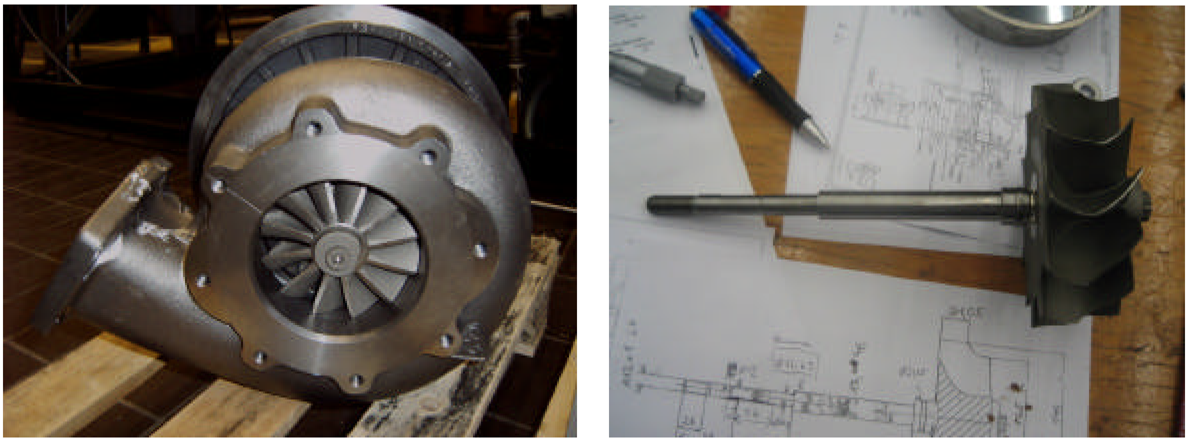


Figure 5-22 Left: specimen of the RCG expansion turbine
Right: specimen of the turbine wheel of the RCG expansion turbine

Because this turbine is normally fitted on a stoichiometric gas engine it can handle turbine inlet temperatures (TIT) of up to 1000°C which is perfect for the RCG. For operation on bio-fuels, most important features of radial turbines are that they are more robust and much cheaper then the multistage axial turbines that are normally fitted in conventional gas turbines. The radial turbine is less vulnerable to damage form particles in the hot gas stream. Also the radial turbine has no cooling holes that can clog. Finally, because it is easier to manufacture as a multi-stage axial turbine and because it is produced in higher numbers (because of its turbocharger application), it is relatively cheap. Therefore it can be easily replaced if it is still polluted or damaged because of an aggressive hot gas stream that might occur when bio-fuels are combusted. It is believed that with its robust and radial turbine the RCG will be able to offer a very appealing maintenance concept even when operating with crude bio-fuels such as crude glycerin which results in gas stream containing potassium carbonate droplets.

5.3.5 Waste heat boiler

An RCG will need to have a steam generator that is compact and economic. So even though it will be at the cost of thermal efficiency, it is favourable to operate the boiler at relatively low pressure. This results in high temperature differences between exhaust gas and steam, so that a compact single stage steam generator can be employed.

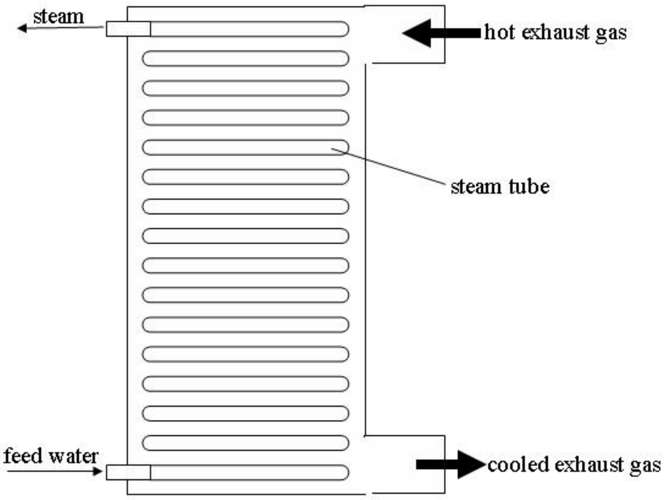


Figure 5-23 Working principle of the once-through steam generator

Furthermore, the steam generator of the RCG needs to be able to start quickly and needs to be able to respond quickly to load changes. Taking all this into account, the once-through steam generator is preferable for the RCG. Figure 5-23 shows the working principle of the once-through steam generator. The hot exhaust gasses that the steam generator takes in come from the turbine exhaust (see figure 1-3) and/or the auxiliary burner. When operating on bio-fuels the exhaust gas stream might contain particles that will stick to the tubes of the steam generator. Therefore in the RCG the casing of the RCG is designed in such a way that the tubes can be easily accessed for cleaning. Furthermore, it should be possible to catch particles and ashes before they enter the steam generator, this could be done by adding an exhaust gas collector that collects the exhaust gas form the turbine and auxiliary burner and then separates particles and ashes from the exhaust gas stream before it is supplied to the steam generator. This could be done by decreasing the velocity of the exhaust gas stream, impaction separation or with (hot) cyclone technology.

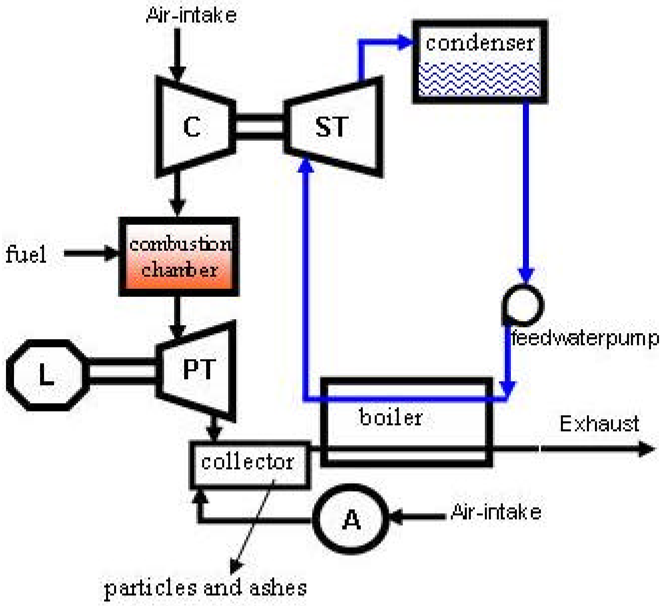


Figure 5-24 Schematic of the RCG with exhaust gas collector that separates particles and ashes

When operating on crude glycerin, the exhaust gas stream will contain potassium carbonate droplets in the steam generator the temperature drops to a level where these salt droplets would become solid. To prevent clogging, the salt droplets need to be separated before they enter the steam tube bundles. The steam generator of the first real-scale (1.2MWe) RCG in 2008 is therefore designed to have an impaction separator that separates the alkaline salts right after the turbines in a collector (see figure 5-25). On the left of figure 5-25, the combustors are shown. Only 2 of the 4 combustors are shown for clarity of the picture. Also other components, such as parts of the steam generator (boiler) are left out for clarity reasons, so that one can look into the center of the boiler. Pressurized air will be delivered to the combustors by the steam turbine driven turbo compressor (not shown) of the RCG.

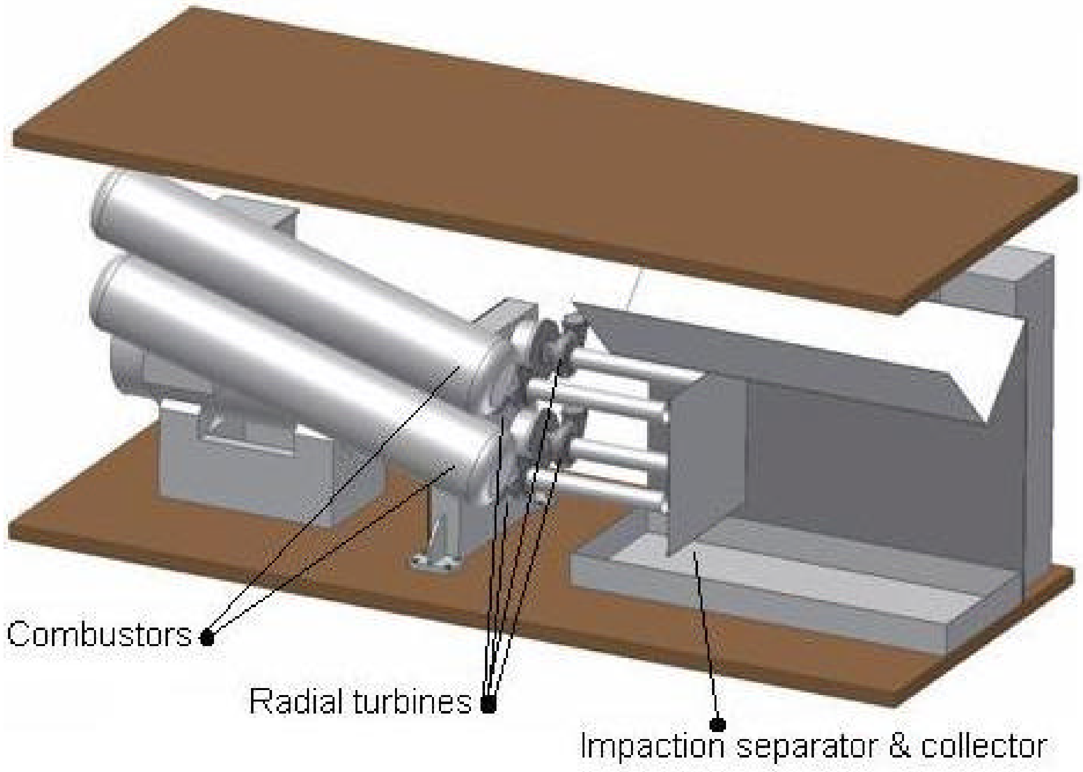


Figure 5-25 Design of the RCG with exhaust gas collector that separates particles and ashes with the impaction principle

Figure 5-25 shows that the RCG features really long combustors to ensure complete combustion of crude bio-fuels. The radial turbines are supplied with hot pressurized combustion gasses from the four combustors. All four turbines are coupled to one gearbox, thus driving one large generator. The expanded exhaust gasses of the turbines are lead to the center of the steam generator where the potassium salts will be separated from the exhaust gas stream by an impaction separator. This option is only for operation on crude glycerin; for crude bio-fuels the RCG will be fitted with hot cyclones, also in the center of the steam generator. After the separation of ashes, the exhaust gasses flow to the steam generator tube-bundles, which are placed on opposite sides of the separator (only one side is shown in figure 5-25).

6 Economical feasibility

6.1 Conventional CHP configuration

6.1.1 Expected investment and operation costs

For the calculation of the economical feasibility of the application of bio-fuels in (new) gas turbines, several assumptions have to be made, such as investment costs, maintenance costs, electrical efficiency and fuel price. However, specific cases will all be different due to varying local circumstances and the large variety in specs of available gas turbines. Calculating with average values of gas turbine specifications that are typical for certain shaft powers, it will be possible to give a general insight in the economical feasibility of bio-oils in gas turbines. It follows from chapter 5 that industrial gas turbines are most suited for running on bio-oils because they are rugged and often are available with separate burners that can be elongated to ensure enough residence time. Figure 6-1 shows the average electrical efficiency versus electrical power of typical industrial gas turbines in the range $1MW_e$-$50MW_e$.

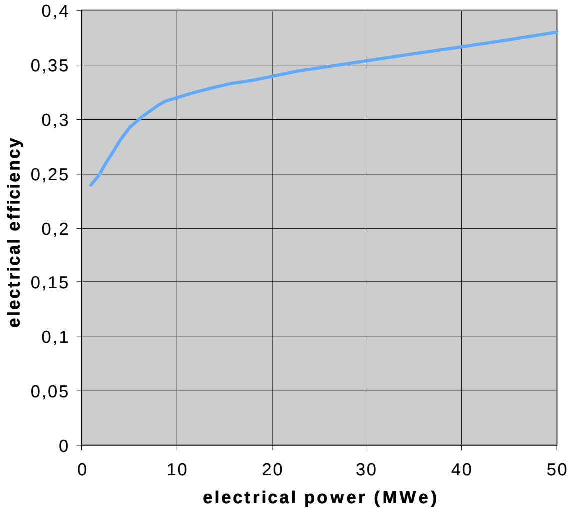


Figure 6-1 Average electrical efficiency versus electrical power of typical industrial gas turbines

One might expect that the investment costs per kW_e will be higher for gas turbines with higher electrical efficiency. This is not the case, in fact they decrease (on average) with rising electrical power (shaft power). Figure 6-2 shows the average investment costs of a complete industrial gas turbine installation with a heat recovery steam boiler that will be assumed for the economical feasibility calculation.

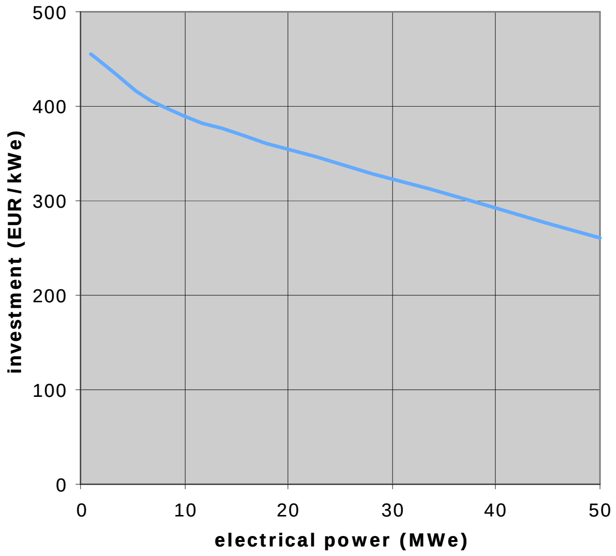


Figure 6-2 Average specific investment costs versus electrical power of CHP industrial gas turbine installations

Considering the previous chapters it will be assumed that industrial gas turbines (after modification) are able to run on relatively clean bio-oil with an energy content of 37MJ/kg and an average price of €500,-/ton. The maintenance and insurance costs for a combined heat and power (CHP) gas turbine are estimated at €0,02/kWh.

6.1.2 Payback time conventional CHP configuration

Figure 6-3 shows the calculated payback time assuming an additional green electricity subsidy of €0,08/kWh (also referred to as SDE in the Netherlands) and EIA (Dutch Energy investment tax deduction of around 11% of total investment). Furthermore the spreadsheet that was used for these calculations calculated with an availability of 8000 hours per year. It can be seen that a fixed SDE of

€0,08/kWh would result in unprofitable operation of new gas turbines below 5 MW_e and a disproportionate advantage for the larger installations. If use of bio-oil over the entire electrical power range is desired, then the SDE revenue should be installation size dependant. Furthermore the payback time is very vulnerable to changes in base load electricity supplier revenues and fuel price. To ensure a certain payback time it would be best if the SDE revenue would somehow compensate for this.

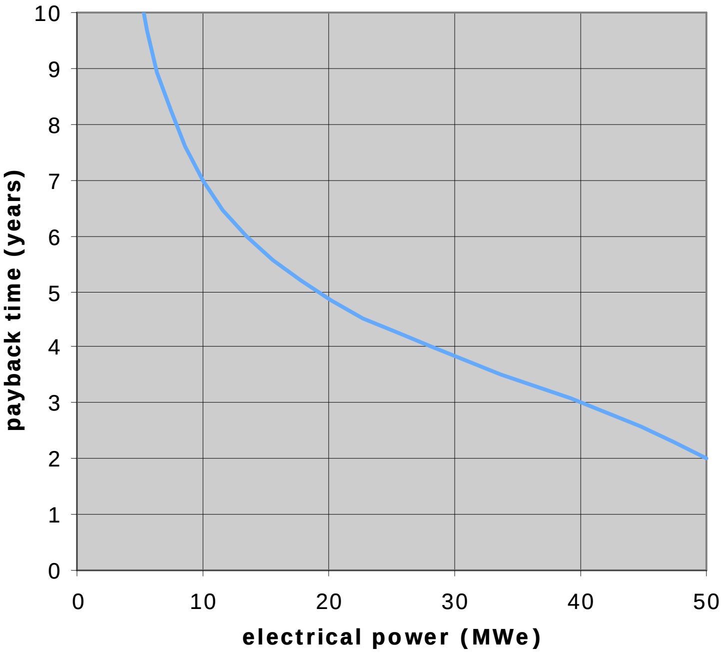


Figure 6-3 Payback time versus electrical power of CHP industrial gas turbine installations assuming an SDE revenue of €0,081/kWh

6.1.3 Payback time of conventional CHP configuration with retrofit bio-fuel combustors

From the preceding chapters it follows that it is also possible to adapt existing industrial gas turbines for bio-oil. The payback time of retrofitting prolonged combustion chambers with preheating and installing a fuel tank was also calculated. This will typically result in a very interesting payback time of approximately 1 year, if it is assumed that the payback time is only related tot the investment for the adaptation to bio-fuel. Of course this does not take into account the remaining expected life-time and current depreciation status of the existing gas turbine. This should be considered for every specific case. However, it can be concluded that applying bio-fuels in existing gas turbines with a retrofit combustor will offer a very interesting combination of low financial risk (relatively low investment costs) with a short payback time. The best candidates for retrofitting will be robust low-tech industrial gas turbines with uncooled expansion turbines, because then the least technical problems and maintenance costs are to be expected. A condition for retrofitting is however, that there will emerge companies that will make retrofit bio-fuel combustors available on this niche-market.

6.2 Rankine Compression gas turbine (RCG)

6.2.1 Expected investment and operation costs

The RCG will be available in the electrical power range of 1-10MW$_e$. Figure 6-4 shows the average electrical efficiency versus electrical power of the RCG.

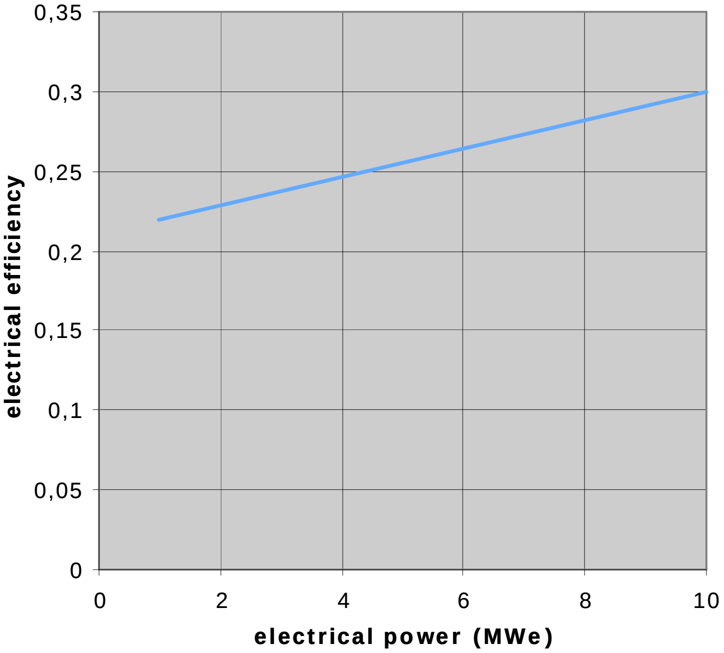


Figure 6-4 Average electrical efficiency versus electrical power of the RCG

The electrical efficiency of the RCG is comparable or even somewhat lower than that of high-end gas turbines. One might expect that the RCG would have higher efficiencies because it is a combined cycle; however the RCG is designed to give acceptable efficiency with very robust components. The investment costs of the RCG (see figure 6-5) are considerably higher then that of the conventional gas turbine, because the RCG comprises a steam turbine cycle. The robust design allows the RCG to run on crude bio-oils. It will be assumed that the RCG is able to run on crude bio-oil with an energy content of 37MJ/kg and an average price of €250,-/ton. The maintenance and insurance costs of the RCG are estimated at €0,02/kWh, just like the conventional gas turbine.

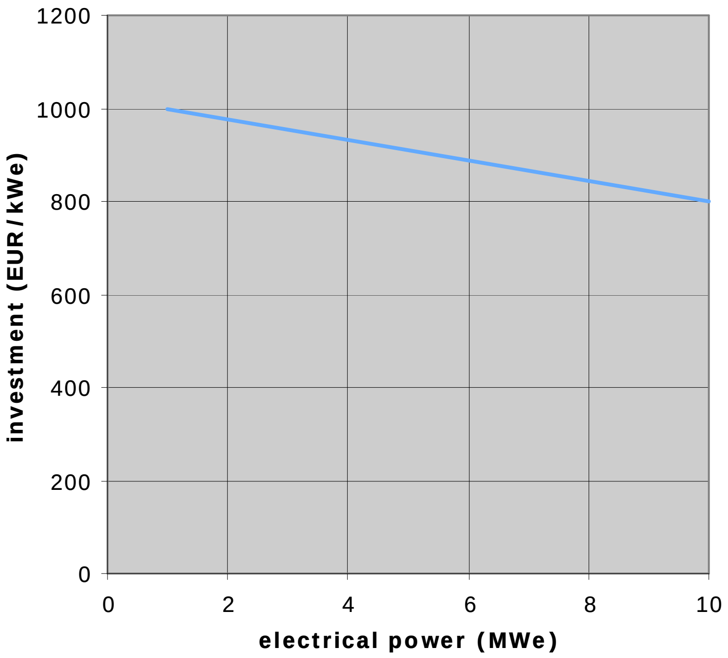


Figure 6-5 Average investment costs versus electrical power of the RCG

6.2.2 Payback time

Figure 6-6 shows the calculated payback time of the RCG assuming an SDE of €0,08/kWh and EIA, the same as for the conventional system. It can be seen that a fixed SDE of €0,08/kWh would again result in disproportionate payback times. Again, just like with the conventional gas turbines, the SDE revenue should be installation size dependant. Although one might not expect it due to the high investment costs and moderate electrical efficiencies, the payback time of the RCG is still appealing. This is mainly due to the ability of the RCG to run on low-cost crude bio-oil.

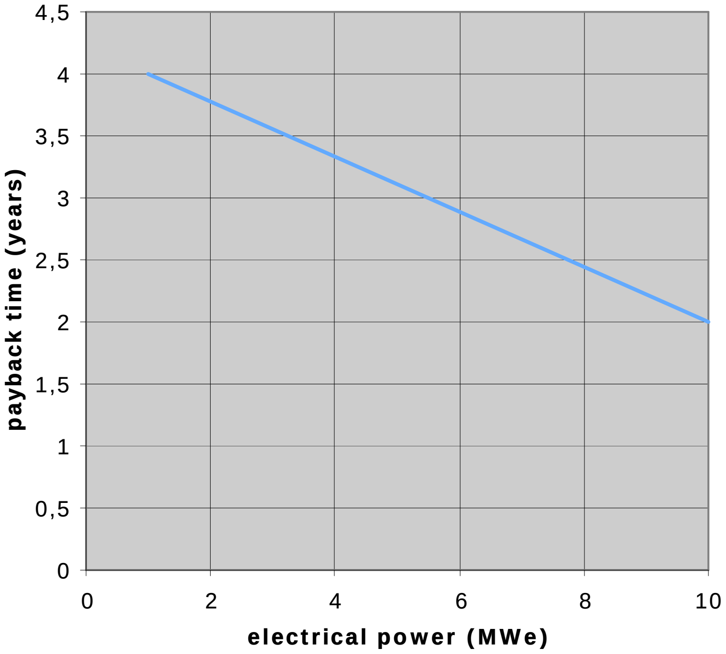


Figure 6-6 Payback time versus electrical power of the RCG assuming a SDE revenue of €0,081/kWh

7 Conclusions

Existing gas turbine classification

Most stationary gas turbines are designed for the use of natural gas and light diesel fuel oil only. The overwhelming majority of the existing gas turbines is operated on natural gas only but some may be also equipped with dual fuel oil burners. These, mainly aeroderivative, gas turbines have very strict fuel oil requirements (f.i. < 1 ppm Na+K & < 0,01% ash, low viscosity).

However, some industrial type gas turbines are also able to use high ash and high viscosity heavy fuel oil, residual oil and sometimes even crude oil. Common industrial types are f.i. the GE frame 7& 9 series, the Siemens SGT 500, Hitachi 25 and the Alstom GT13. When determining the feasibility of bio-oils combustion in gas turbines the distinction between these two different gas turbine types has to be made: some industrial types should be capable of 100% (retrofit) bio-oil combustion while for most of the other gas turbines this may prove to be much more difficult.

Bio-oil quality, refining and treatment

Suitable bio-oils include refined palm oil, refined soy oil, rapeseed oil and refined animal fat (from a technical point of view). The prices of the first and the last mentioned are most attractive. Especially the bio-oil quality proves be crucial. This report shows that extensive bio-oil refining often is a necessity. At the same time, bio-oil storage and bio-oil filtration require special attention in order to guarantee sufficient bio-oil quality. A bio-oil quality control system should at least include the following important parameters: Conradson carbon residue, oxidation stability, polymer content, contamination, phosphorus and ash content and acid value.

Bio-oil atomisation and combustion

Modelling and operational experiences with diesel engines have shown that fuel atomisation can be the critical parameter for bio-oil firing in existing gas turbines. The two main fuel characteristics which impact atomisation are viscosity and surface tension. Although bio-oils can display quite some diversity, bio-oil droplets typically have a 2-3 times bigger radius when compared to diesel droplets under the same injection conditions. The time needed for evaporation and combustion of droplets of equal composition can be estimated while applying the so called R^2-law. This means that bio-oil droplets may typically burn 4 to 9 times slower than diesel droplets (only regarding droplet size). As combustor residence times are typically very short, bio-oil firing in a gas turbine which was designed for diesel, may result in insufficient combustion time, hot path damage and too high UHC emissions. This is why it is recommended to execute a technical feasibility study prior to bio-oil conversions in an existing gas turbine. In some cases, it may be necessary to adjust the existing nozzles and/or injection pressure, to implement start/stop procedures using diesel or to have a reduction of the maximum rated power.

Emissions

Supposing a good conversion of the fuel line to bio-oil and good operation of the gas turbine, the emissions with bio-oil may be similar when compared to diesel or fuel oil. The emission of acidifying SO_2 is nearly absent as bio-oils contain very little sulphur.

Future outlook

The economic evaluation has shown that pay-back times within 1-3 years can be realised provided additional cash flow due to green electricity sales can be generated. The application of bio-fuels in existing gas turbines with a retrofit combustor will offer the shortest payback time (1 year) and the lowest financial risk, therefore retrofitting seems perfect for gaining more practical experience on short term.

The authors of this report are convinced that the firing of bio-oil in stationary gas turbines will become a proven technology, just like the already successful transition within the stationary diesel engine sector. We observe that OEM gas turbine manufacturers will start approving bio-oil conversions for some industrial types while new, more versatile and robust, gas turbine models are being tested and developed by innovative smaller companies like for instance Heat Power.

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APPENDIX B Sauter mean diameter droplet calculations

Matlab-files for Sauter mean diameter droplet calculations of chapter 5:

```
% This Matlab script calculates the influence of increasing nozzle pressure
% difference at T=360K, d=0.4mm
clear all;

% input the coefficients for the expressions of liquid viscosity, density
% and surface tension
A=-18.2152;
B=4.2305e+3;
C=2.8705E-2;
D=-1.8648E-5;
E=0.34908;
F=0.24902;
n=0.15410;
Tc=723;
G=124.793;
m=1.2222;

% known parameters
T=360;
d=0.4e-3;

mu1=1e-3*10^(A+B/T+C*T+D*T^2);
rho1=1e+3*E*F^(-(1-T/Tc)^n);
sigma=1e-3*G*(1-T/Tc)^m;

rho2=1.1614;
mu2=184.6e-7;
C0=0.9;
```

```
% creating arrays (will be used in plot)
k=1;
U=zeros(72,1);
DeltaP=zeros(72,1);
Flowrate=zeros(72,1);
SMD1=zeros(72,1);

% calculation with different deltaP
for deltaP=2.9e+6:0.1e+6:10e+6

    u=sqrt(2*deltaP/rho1);
    flowrate=0.25*rho1*pi*d^2*u*C0;
    Re=rho1*u*d/mu1;
    We=u^2*rho1*d/sigma;
    SMD=0.38*Re^0.25*We^(-0.32)*(mu1/mu2)^0.37*(rho1/rho2)^(-0.47)*d;

    U(k)=u;
    DeltaP(k)=deltaP;
    Flowrate(k)=flowrate;
    SMD1(k)=SMD;
    k=k+1;
end

% plot results
deltaP=linspace(2.9e+6,10e+6,72);
plot( DeltaP/1e+5,U,'k','LineWidth',1.8 );
grid;
xlabel( 'Nozzle Pressure Difference (bar) (T=360K  d=0.4mm)','FontSize',12
);
ylabel( 'Minimum Nozzle Exit Velocity (m/s)','FontSize',12,'Rotation',90 );
figure;
plot( DeltaP/1e+5,Flowrate,'k','LineWidth',1.8 );
grid;
```

```
xlabel( 'Nozzle Pressure Difference (bar) (T=360K  d=0.4mm)','FontSize',12
);
ylabel( 'Fuel Flow Rate (kg/s)','FontSize',12,'Rotation',90 );
figure;
plot( DeltaP/1e+5,SMD1*1e+6,'k','LineWidth',1.8 );
grid;
xlabel( 'Nozzle Pressure Difference (bar) (T=360K  d=0.4mm)','FontSize',12
);
ylabel( 'Sauter Mean Diameter of Spray Droplets
(micron)','FontSize',12,'Rotation',90 );


% This Matlab script calculates the influence of varying fuel temperature
% with a constant nozzle hole diameter d=0.4mm
clear all;

% input the coefficients for the expressions of liquid viscosity, density
% and surface tension
A=-18.2152;
B=4.2305e+3;
C=2.8705E-2;
D=-1.8648E-5;
E=0.34908;
F=0.24902;
n=0.15410;
Tc=723;
G=124.793;
m=1.2222;

% known parameters
d=0.4e-3;
rho2=1.1614;
mu2=184.6e-7;
```

```
C0=0.9;

% creating arrays (will be used in plot)
k=1;
U=zeros(19,1);
DeltaP=zeros(19,1);
Flowrate=zeros(19,1);
SMD1=zeros(19,1);

% calculation with different T
for T=300:10:480
    mu1=1e-3*10^(A+B/T+C*T+D*T^2);
    rho1=1e+3*E*F^(-(1-T/Tc)^n);
    sigma=1e-3*G*(1-T/Tc)^m;

    u=sqrt( 40.3*sigma/(rho2*d) );
    deltaP=0.5*u^2*rho1;
    flowrate=0.25*rho1*pi*d^2*u*C0;
    Re=rho1*u*d/mu1;
    We=u^2*rho1*d/sigma;
    SMD=0.38*Re^0.25*We^(-0.32)*(mu1/mu2)^0.37*(rho1/rho2)^(-0.47)*d;
    U(k)=u;
    DeltaP(k)=deltaP;
    Flowrate(k)=flowrate;
    SMD1(k)=SMD;
    k=k+1;
end

% plot results
T=linspace(300,480,19);
plot( T,U,'k','LineWidth',1.8 );
grid;
xlabel( 'Temperature (K) (d=0.4mm We=40.3)','FontSize',12 );
```

```
ylabel( 'Minimum Nozzle Exit Velocity (m/s)','FontSize',12,'Rotation',90 );
figure;
plot( T,DeltaP/1e+5,'k','LineWidth',1.8 );
grid;
xlabel( 'Temperature (K) (d=0.4mm We=40.3)','FontSize',12 );
ylabel( 'Nozzle Pressure Difference (bar)','FontSize',12,'Rotation',90 );
figure;
plot( T,Flowrate,'k','LineWidth',1.8 );
grid;
xlabel( 'Temperature (K) (d=0.4mm We=40.3)','FontSize',12 );
ylabel( 'Fuel Flow Rate (kg/s)','FontSize',12,'Rotation',90 );
figure;
plot( T,SMD1*1e+6,'k','LineWidth',1.8 );
grid;
xlabel( 'Temperature (K) (d=0.4mm We=40.3)','FontSize',12 );
ylabel( 'Sauter Mean Diameter of Spray Droplets
(micron)','FontSize',12,'Rotation',90 );
```