Biofuels – Challenges and Opportunities for Gas Turbines

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The trend towards small-scale decentralized power generation has led to a growing interest to utilize fuels that are locally available. This trend, together with the wish to find alternatives for fossil fuels, has led to an increasing interest to operate gas turbines on biofuels. Biofuels refer to fuels derived, directly or indirectly, from organic matter and include syngas, biogas, pyrolysis oil and bioethanol. Biofuels differ significantly from conventional fossil fuels, such as natural gas and diesel, as they have low energy density, different chemical composition and might contain challenging contaminants. These aspects have a direct and significant impact on the gas turbine operation in terms of the combustion process, emissions and equipment life time. To meet the increasing demand to utilize biofuels, OPRA Turbines has developed and introduced the OP16-3C gas turbine. The OP16-3C, rated at 1.85 MWe, has been developed to burn liquid and gaseous biofuels and is based on the well-proven OP16 gas turbine configuration. This paper will start by presenting an overview of the potential for biofuel utilization in Europe and how the opportunities and possibilities differ throughout the continent. Next, the paper will review the technical challenges associated with operating gas turbines on different biofuels and how these can be addressed with current and future technologies. In addition, the Medium Combustion Plant (MCP) Directive, which regulates the pollutant emissions from combustion plants with a thermal input of 1-50 MW, will be discussed in relation to the combustion of biofuels. Throughout the paper, data from tests in the OP16-3C combustion chamber will be used to explain the effects of various liquid and gaseous biofuels on the combustion process and pollutant emissions.

1 Introduction

The trend towards small-scale decentralized power generation has led to a growing interest to utilize fuels that are locally available. Especially in Europe where natural sources of fossil fuels are limited and regulations push towards sustainable alternatives. This results in the exploration of biofuels which are derived, directly or indirectly, from organic matter. As an example, one can think of the following fuels: syngas, biogas, pyrolysis oil, biodiesel and bioethanol. Most of these bio-derived fuels contain properties which make them challenging to store and use. Contaminants, quality deterioration and low energy content are points which require additional attention and checks, before biofuels are used in power generation applications.

Together with the previous notes, gas turbines are known to operate on a vast amount of different fuels and generally well-suited in fulfilling the wish for small-scale decentralized power generation. Especially in combined heat and power (CHP) applications where a gas turbine can lead to an efficient system reaching heat utilization up to 90% of energy content of the fuel. These advantages fit well in the sustainability targets of the EU for 2020 to reduce emissions and increase fuel efficiency (1). The locally available biofuels will play an important role in achieving these targets. At this moment, they consist mainly of first generation biofuels which are also already part of the transportation energy chain for over several years (2). The focus on energy carriers of the second generation and even next generation of advanced biofuels is increasing due to European Commission (EC) cap of 7% on first generation biofuel production (2). Based on the listed biofuels reported by the European Biofuels Technology Platform (EBTP) (3), this opens the opportunity for gas turbines in power generation applications. Examples of these second generation and advanced biofuels are pyrolysis oil, cellulose ethanol and various (ultra) low calorific variants of biogas or syngas.

This paper uses the experience and the development work of the OP16 gas turbine in relation to biofuels. Throughout the paper, data and test results of the OP16-3C combustion chamber will be used to explain the effects of various liquid and gaseous biofuels on the combustion process and pollutant emissions. First, the opportunities of utilizing biofuels will be discussed while differentiating between gaseous and liquid fuels. This is followed by the technical challenges while operating gas turbines on different biofuels. A large contributor to these challenges is the fuel quality, which is affected by contaminants and dilutants. This is examined in more detail for general biofuel cases. In addition, the Medium Combustion Plant (MCP) Directive, which regulates the pollutant emissions of gas turbines with a thermal input of 1-50 MW, will be addressed in relation to biofuels. Overall, this paper will contribute to a better understanding of the opportunities and challenges of utilizing biofuels in gas turbines.

2 Gas turbine fuels: Biofuel opportunities

In the European Union (EU), the Council and Parliament has agreed on the 'climate and energy package'. This agreement embodies the commitment to reduce the greenhouse gas (GHG) emissions by 20% compared to the 1990 levels, together with a 20% improvement in energy efficiency compared to 2020 forecasts and a 20% renewable energy target for the EU by 2020. These commitments are reported to be well on track in February 2017, but still need effort from all members (4) (5). It is also reported that the greatest potential in reducing emissions is in the electricity generation sector. The technical solutions are found in reducing industrial user consumption, household consumption and in decreasing transmission losses. For reference, the transmission and distribution losses of electricity in Europe are on average ~6% (6). Further, greater investment in low-carbon electricity generation such as renewable energy is necessary. Households and services also have an important role in reducing GHG emissions, especially from heating systems. The agricultural sector with its intensive farming is responsible for about half of all non-CO_2 emissions. These emissions consist mainly of methane which has a reduction potential if used for combustion. Together with the 2020 EU goals, Europe committed itself to contributing to limit the global rise in temperature by 1.5° at the 2015 Climate Change Conference in Paris. That commitment and the new EU targets set for 2030 drive the implementation of renewables and focus on energy efficiency.

Based on these areas, with potential improvements stated in the climate and energy package and the newly set targets and commitments, gas turbines can fulfill a great role in achieving these targets and the ones that are around the corner. Utilizing biofuels in a decentralized gas turbine CHP system cover most of the abovementioned focus points. The power can be produced locally, which decreases the losses. In addition, the heat can be utilized in local industrial processes or heat distribution systems for household and utility heating. The replacement of obsolete fossil fuel boilers with efficient renewable heating CHP systems is expected to be one of the main initiatives presented by the EC for the post 2020 renewable energy directive (2).

While renewable power generation by solar and wind is increasing (4), combustibles are still an important part of the energy chain. Small and medium enterprises that rely on heat and power on demand to control their processes, will seek for solutions that are meeting the European targets and are reliable. Gas turbines are in general well-suited to run on a large variety of fuels. The design makes it also possible to be fuel flexible and to run in different modes that can combine conventional and biofuels at the same time. Dual-fuel operation, bi-fuel operation or blending biofuels with conventional fuel are possibilities to reduce the operational risk if biofuel availability or quality are not meeting the requirements. Bi-fuel will feed two fuels to the combustion process simultaneously, while in dual-fuel set-up one can switch between two different fuels (liquid-gas, gas-gas or liquid-liquid) during operaton. Another advantage of gas turbines is that biofuel types that are considered a (ultra-) low caloric fuel with a low Lower Heating Value (LHV) can result in an increase in gas turbine performance due to the added mass flow in the cycle (7). Gas turbines also show potential in utilizing the biofuels that are not attractive to upgrade to transportation fuels or to be dropped into the current energy infrastructure. Especially now that the focus will shift from first generation biofuels to the second generation and other advanced advanced biofuels, fuels will be created where the gas turbine cycle will be the technical preference. The next section will provide some background information about biofuels and the current European feedstock streams.

3 Biofuels

Biofuels are fuels that are derived from any vegetable matter out of agricultural, forestry and waste streams which do not fall under prehistoric 'fossil' organic matter. The increase of biofuel consumption and production in Europe is mainly driven by the renewable energy and GHG targets. Within Europe there are several potential feedstocks for biofuel production. At this moment, biofuels are mainly produced out of edible crops such as grain, other sugar containing crops and vegetable oils. These are known as first generation biofuels, like bioethanol and biodiesel, and are part of modern sustainability discussions. The competition with areas that are designated for food production or the conservation of nature are one of the concerns. Therefore, EU is focusing on the second generation biofuels to meet its targets and also by enforcing a cap on the biofuel production of the first generation type. The preferred result will be that the most efficient production processes will be selected (2). Second generation biofuels are fuels produced from non-food and non-fossil materials. They have the potential benefits of using waste residues and abandoned land. All over Europe there are densely populated areas which results in a relative constant waste streams. These can be used to produce biogas and liquids. A disadvantage of using waste streams is that the recovery of its energy content might counteract the effort of recycling the waste (8). Another feedstock for second generation biofuels is wood and its derived residues. This feedstock is widely available in the northern and eastern part of Europe. It is necessary to use a sustainable approach, which takes deforestation into account, because the current European production cannot keep up with current demand (2). Wood can be converted into solid, liquid and gaseous biofuels and transported in a relatively stable form as liquid, wood or pellets. The latter is of importance if the fuels need to be transported and stored while internationally traded, in contrary this is not feasible for some other low energy density feedstocks as waste or manure (9).

3.1 Gaseous biofuels

The first classification of different gaseous fuels can be done based on their energy density as shown in Figure 1. The energy density of gaseous fuels is mainly influenced by the number of hydrocarbons (methane, ethane, etc.), dilutants (e.g. nitrogen and carbon dioxide), carbon monoxide and hydrogen in the fuel. One can see the clear difference between conventional fossil fuels like natural gas and the low and ultra-low calorific gas types. If the LHV drops below 25 MJ/kg, it is defined as a low calorific fuel, when it drops even below 15 MJ/kg it is considered an ultra-low calorific fuel (1). Gaseous biofuels will in general fall under the low and ultra-low calorific fuels without any significant purifying steps. The low LHV of the fuels result in completely different combustion properties compared to conventional fuels. If the energy carrying part of the fuel consists mainly of hydrogen and carbon monoxide, the fuel behaves different than methane based fuels. This is for example the case for syngas were the carbon monoxide part requires a long reaction time and hydrogen reacts fast. Produced biogas will in general also contain a significant amount of dilutants, which will decrease the temperature of the flame. This will bring additional challenges during turbine operation which will be discussed in a later section. Designated combustion hardware which can handle these challenges is required, if one wants to move forward and utilize (ultra-) low calorific fuels. One example is the OP16-3C combustor, which is designed to cope with the challenges and successfully tested on several syngas and biogas fuels (10).

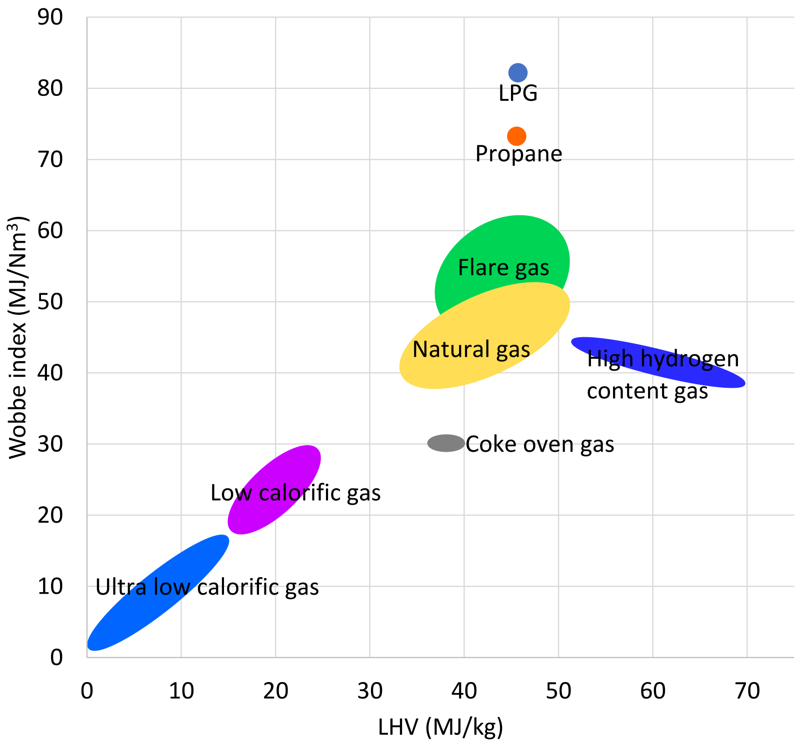

Figure 1: Classification of gaseous gas turbine fuels

The production of gaseous biofuels in Europe mainly focusses on the production of biogas by means of fermentation which is a well understood process. This will result in a methane based gas with roughly 50-60% of methane and carbon dioxide as its main diluent (2). The second generation feedstocks like waste, wood and residues can increase the opportunities for gaseous biofuel production by means of gasification. The latter will result in syngas, consisting mainly of hydrogen, carbon monoxide and dilutants. The biogas sector in Europe is very diverse and it mainly depends on national priorities. The production of biogas is primarily seen as way of managing waste, a method to produce renewable energy or a combination of the two. For example, Germany generates over 90% of its biogas from the fermentation of agricultural crops and residues, while the UK and Ireland mainly use landfill and sewage sludge gas. Biogas production is still increasing, but it really depends on financial attractiveness of the country where the plant is located. Almost all the methane based biogas is utilized to produce power and heat. An opportunity for gas turbines is to step in before the biogas is purified to the natural gas grid quality, it can already be used in its low calorific form which reduces an additional step in the process.

3.2 Liquid biofuels

Similar as for the gaseous fuels, liquid fuels can be also classified in different groups depending on its source or specifications. The different groups can be categorized based on their LHV as well and one should note the conventional fossil fuels like petrol and diesel are in the higher range of the energy density scale. In general, all the bioderived fuels like methanol, ethanol, pyrolysis oil and biodiesels will have a lower LHV compared to the fossil alternatives as shown in Figure 2. The chemical properties of the fuel itself is the main cause of the lower LHV and in case of pyrolysis oils, water content is not contributing to the calorific value and is therefore a diluent. Blending bioliquids into transportation fuel like petrol and diesel is already common practice in the EU, but makes the used fuels like ethanol and biodiesel less attractive for utilization in gas turbines. Technically there are no real drawbacks while combusting ethanol and biodiesel; it will even increase the performance of a gas turbine due to the increase in mass flow. The EU is regulating the import by financial measures for ethanol and an increase in availability on the short term is unlikely (2). On top of that, the focus on second generation biofuels is expected to limit the use of technically suitable transportation biofuels in stationary CHP applications. The advanced and second generation bioliquids are the hydrogenated vegetable oils (HVO), made from waste oils and fats and cellulose ethanol. HVO can directly replace petroleum fuels such as kerosene which makes it a valuable stream. Alcohols like methanol and ethanol can be produced from multiple feedstocks and in case of ethanol, mainly first generation feedstock is used. On the other hand, cellulose ethanol shows great potential because it can use second generation feedstock like wood and residues for ethanol production. Biomethanol made from syngas or glycerin, that comes as a byproduct of biodiesel, will also be a suitable fuel, but again it is a candidate to blend in conventional transportation fuels to boost its knocking properties. This leaves the pyrolysis oil derived from wood or its residues which is challenging fuel due to its higher viscosity and complex composition. These properties with their corresponding technical solutions, like fuel heating and larger combustor volumes, point in the direction of industrial applications. The OP16-3C combustor was designed with pyrolysis oil combustion in mind and ran a successful test campaign with this fuel (11).

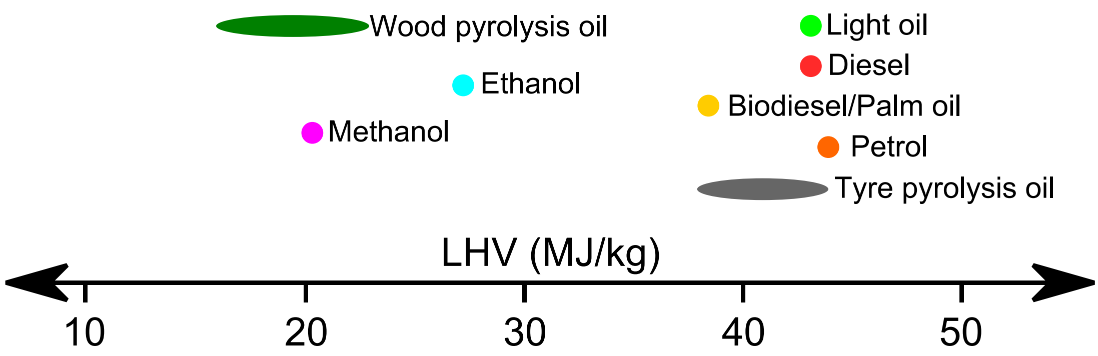

Figure 2: Classification of liquid gas turbine fuels

4 Gas turbine fuels: Biofuel challenges

Compared to conventional, hydrocarbon based, fuels the biofuels have certain additional challenges. Each biofuel is different due to their origin and production methods. However, there are some common challenges. Typically, the biofuels have low energy density (i.e. low LHV), which require the standard equipment to be modified and/or re-designed to accommodate the higher fuel flow. In addition, the lower energy density typically result in a lower flame temperature. This results in that the time to ensure complete combustion increases, which requires hardware modifications. The properties and chemical composition varies significantly between various biofuels. This is because the biofuels are derived from a large range of feedstock, which has a direct influence on the properties. This requires the combustion systems to have a certain degree of flexibility to enable the use of different biofuels without major hardware changes. This is also required to handle variation in biofuel composition because of feedstock fluctuations.

A non-technical issue is the transportation and distribution of the biofuels. Some biofuels (e.g. syngas) can be utilized at the plant where they are produced. However, other biofuels such as pyrolysis oil, requires transportation to the end-user. This requires distribution networks to be developed to enable the use of these biofuels on large scale.

The biofuels contain to varying degree impurities and contaminants, which poses challenges for reliable operation and low maintenance costs. The chapter will continue with a discussion about the fuel quality and its challenges for both gaseous and liquid biofuels.

4.1 Gaseous biofuels

This section will discuss the challenges of gaseous biofuels. Both fuel quality and operational challenges will be discussed.

4.1.1 Fuel quality and contaminants

Before deciding to operate on a biofuel, several aspects need to be evaluated to determine whether it can be used in a particular gas turbine and/or if cleaning of the fuel is necessary. In this section a brief overview of the most characteristic properties of these fuels and the challenges for gas turbine operation are given.

Water in gaseous biofuels is common due water present in the feedstock. The amount of water is directly correlated with the temperature of the gas and the production method. The water can cause the fuel supply systems to corrode and care must be taken when designing the system to avoid this. This is of course typically done by selecting materials with great resistance to corrosion. Water in the fuel increases the dew point and requires the fuel to be pre-heated to avoid the fuel to condensate. A knock-out drum can also be used to remove liquid from a gaseous fuel. If the fuel condensates and droplets are formed it might lead to unstable combustion process and severe hardware damage, as the system is designed to handle the fuel in gaseous form.

Hydrogen sulphide (H_2S) in the fuel results in corrosion and SO_x emissions. Biogas, due to anaerobic microbial degradation of organic substances, will contain a varying amount of H_2S depending on the feedstock used. The concentration of H_2S can range from a few ppm in facilities processing renewable resources to several thousand ppm when fermenting liquid manure, biological waste and food remains. The sulphur can, in combination with sodium and potassium, form alkali sulphates during the combustion process. These sulphates can condensate when the combustion gas cools down downstream the combustor and can form a corrosive layer in the turbine section. This is called hot corrosion and can greatly reduce the life time of the hot flow path components. To reduce the amount of H_2S in the biogas several techniques can be used; activated carbon filters, low level oxygen dosing into digester head space, external biological scrubber towers and ferric chloride dosing into the digester.

Trace metals might be present in the biogas production process. Trace metals, such as lead, vanadium, calcium and magnesium might originate from the feedstock or are added to the biogas production process. Trace metals are known to improve the production of biogas in anaerobic processes (12). On the other hand, these trace metals tend to convert into molten compounds during combustion. These compounds solidify in the hot flow path of a gas turbine causing fouling and for some trace metals (e.g. vanadium and lead) also hot corrosion. The presence of very small amounts of trace metals might already result in a very significant decrease of component lifetime. (13)

Siloxanes are chemical compounds that can be found in various products such as cosmetics, deodorants, food additives and certain soaps. They are often used to smooth or soften cosmetic products, or as a chemical building block for silicone-based rubbers and oils. Therefore, biogas and landfill gas will typically contain some siloxanes depending on the feedstock. During the combustion oxides of silicon (SiO_2) will appear. This is essentially sand and might result in damages on the turbine blades due to abrasive wear. If the amount of siloxanes is too high a purification of the biogas can be done. There are several ways of removing siloxanes including, adsorption, absorption and condensation.

Tars are heavy hydrocarbons formed during the gasification process. Tars can cause fouling on the turbine components, such as blocking vital cooling holes and nozzles. Tars also require a long time for complete burnout.

4.1.2 Operational challenges

Although gas turbines can generally accept a wide range of fuels, there is certain operational challenges when operating gaseous biofuels in gas turbines. However, these operational challenges differ from the challenges found in gas engines, which suffer from preignition, knock, backfire and fouling issues. Since gas turbines operate with a continuous flame, preignition, knock and backfire are not an issue. Therefore, gas turbines can also operate on fuels which are not suitable for gas engines and more variation in fuel quality can be allowed.

Due to the lower energy density, the equipment needs to be sized to allow the higher fuel flow. For the fuel systems, this is straightforward as long as there is sufficient space to increase the valve sizes and pipe diameters. It might be more challenging to ensure that the fuel has sufficient time to completely combust due to their lower flame temperatures and subsequently lower reaction rates. For a gas turbine with can type combustors, such as the OP16 gas turbine, this can be relatively easily done by extending the combustors. The four tubular combustors of the OP16 are mounted in a reverse flow direction. Depending on the application, the engine will be equipped with a specific type of combustor. The conventional diffusion type combustor (3A) is capable of operating on a wide range of gaseous and liquid fuels, whereas a DLE combustor (3B) is specifically designed for low emission operation on natural gas. The low calorific fuel combustor (3C) is significantly larger than the 3A and 3B combustor and therefore provides sufficient time for proper burnout of low calorific gaseous and liquid fuels. The combustors and associated equipment needs to be designed or modified to allow efficient operation on a particular fuel. This can mean that gas injectors need to be sized specifically for a certain fuel to allow for stable operation. The Wobbe index is a measure of the interchangeability of gases based on existing hardware. The Wobbe index is defined as the ratio between the higher heating value and the specific gravity. The fuel nozzles (or gas injectors) are designed to operate over a range of pressures. If the Wobbe index falls outside the operating range, the pressure drop over the nozzle will be either too high or too low, resulting in a blow-out of the flame and/or unstable combustion process. A very high pressure drop over the nozzle will also result in excessive fuel compressor requirements.

Before deciding to start operating on these kinds of fuels one needs to ensure the fuel quality is meeting the OEM specification. In case it does not meet it, treatment and cleaning of the fuel must be done. However, cleaning of the fuel is costly and it is therefore of great benefit to utilize biofuels in equipment that has a larger acceptance range of the fuel contaminants. Generally, axial gas turbines are more sensitive for hot corrosion and fouling effects than radial gas turbines. The robust all-radial design of the OP16 gas turbine is less sensitive to impeller blade surface pitting corrosion, foreign object damages and fuel contaminants compared to axial turbines. The OP16 turbine is not using cooling for the hot flow path components. Such intricate cooling geometries are sensitive to damages and fouling. Reduced cooling effectiveness is one of the factors causing gas turbine performance degradation. Since the intricate cooling geometries are not used for the OP16, the gas turbine is less sensitive for performance degradation. In addition, all the hot flow path components are manufactured from materials that are well-suited to prevent hot temperature corrosion; hence, coatings are not required.

One of the most critical aspects of biogas is the supply pressure. Typically, the pressure from the gasification is low and close to the atmospheric pressure. This means that the biogas pressure must be boosted before injection into the combustion chambers. However, due to the larger mass flow the power consumption of the gas compressor can become significant. On the other hand, the additional mass flow will be expanded through the turbine and produce a higher power output. One shall note that the increased mass flow through the turbine might drive the compressor towards surge as the back pressure increases and this must be mitigated. In a study (14) the effect on the surge margin and performance for varying heating values of syngas was investigated. It was found that the net power remains relatively constant for the different heating values, i.e. the additional power needed for the booster can be compensated for by the increase turbine output. Low and moderate gas turbine pressure ratios are beneficial as the requirement for gas boosting is reduced. The OP16 gas turbine features a single stage centrifugal compressor with a moderate pressure ratio of 6.7:1. This pressure ratio reduces the need for gas compression prior to introducing the fuel into the gas turbine.

The gas from the gasification process has typically a high temperature. This put challenges on the gas compressor and control valves as they need to be able to operate with higher temperatures and such valves are not readily available. Alternatively, one can cool the gas, but this should be limited as it is thermodynamically not efficient and it might lead to condensation (dew point issue) and formation of tars.

For the ultra-low caloric biogases, there might be an additional challenge during start-up and low-load operation. Since the fuels are very lean it might not have sufficient energy to sustain the flame during start-up and part-load when the air-to-fuel ratio is higher. To combat this, one can develop technology to use a pilot fuel (conventional high-calorific fuel) during the initial phase of operation. Once the gas turbine has reached an operating point where the biogas can sustain the combustion the pilot fuel can be switched off. For this purpose, the OP16 gas turbine can be equipped in a multiple fuel configuration, whereby, besides biogas or bioliquid, also a high calorific gas or liquid can be used. In this way, the OP16 gas turbine can operate in dual-fuel or bi-fuel mode.

4.2 Liquid biofuels

Similar as for the gaseous biofuels, the liquid biofuels have additional challenges compared to the conventional liquid fuels, such as diesel. Although each liquid fuel is different, the following section will highlight certain common aspects related to the fuel quality and operational challenges.

4.2.1 Fuel quality and contaminants

In this section a brief overview of the most characteristic properties of liquid biofuels are given.

Kinematic viscosity is setting the requirements for pumping and atomization of the fuel. A too high viscosity results in excessive pressure requirement and poor atomization, resulting in incomplete combustion. If the viscosity is higher than maximum allowed one can pre-heat the fuel to achieve a lower viscosity. If the viscosity is too low, the lubricating properties of the fuel might be too poor for the pumps. In this case one need to select different pumps able to operate on low-viscosity fuels.

Polymerization reaction occurs in certain biofuels (e.g. pyrolysis oil) and results in a thickening of the oil. The polymerization is a factor of time and temperature, i.e. a higher temperature and longer storage period increases the polymerization reactions. If the polymerization occurs, there is risk that the nozzles and fuel systems are clogged. Therefore, one needs to be careful when heating these fuels to lower the viscosity as the polymerization might be accelerated.

Water in the fuel is common and the amount depends on the feedstock used. Besides lowering the energy density, the water may cause corrosion on tanks and equipment. In addition, the risk of microbial growth will increase. The microbial contamination can cause blockage of the fuel system, filters and nozzles.

Carbon residues are a measure of the carbonaceous material left when all volatile compounds of the fuel have been vaporized. The carbon can form deposits in the combustor, which can negatively affect the life time and cooling of the hardware. Also, carbon residues as well as tars require more time for complete burnout than the volatile components.

Ash and particles are non-combustible materials in a fuel. Ashes can contribute to wear in the fuel system and plugging of the fuel filters and nozzles. Ash can also typically contain trace metals, which contribute to turbine corrosion and deposits.

Acidity of a fuel can have a significant impact on the lifetime of the fuel system and storage. By a proper material selection, the system should be capable of handling an acid fuel.

Trace metals can be present in liquid fuels based on the feedstock. The contaminants can also be added later during transportation and storage of the fuels. The presence of trace metals contributes to hot flow path fouling and might result in a limited lifetime, as already discussed for gaseous fuels in section 4.1.1.

4.2.2 Operational challenges

The utilization of liquid biofuels has certain challenges that needs to be addressed. One can split the challenges in various sub-groups; fuel preparation, storage, combustion and effect on the hot flow path.

Many of the fuels which have a high viscosity requiring fuel pre-heating. However, pre-heating boils off parts of the fuel, which can result in pump cavitation and/or reduced spray quality. In addition, some fuels, such as pyrolysis oil, are chemically unstable at higher temperatures. Because of this, the fuel can start a polymerization process once heated. This process forms a gummy like substance which will eventually block the fuel nozzle. To limit the preheating requirements, OPRA has developed an air blast nozzle for the OP16-3C that handles fuels with high viscosities with a limited need for pre-heating. This nozzle is resistant to erosion and abrasion by contaminants in the fuel and has good atomization properties over a wide range. The air blast nozzle is by its nature less sensitive for clogging than conventional pressure nozzles.

Time is also affecting chemically unstable fuels, the characteristics of an unstable fuel can change significantly over time. Therefore, one needs to pay close attention to the storage condition of unstable fuel such as to avoid the fuel to start the polymerization. Limited storage time of liquid biofuels is therefore preferred. Many biofuels contain emulsified or free water. This can give problems related to bacterial growth. Once the bacterial growth has started it is almost impossible to get rid of it unless the equipment (e.g. storage tanks and piping) is replaced. The bacterial growth can lead to clogging of the fuel filters and the injection nozzles.

The combustion process is also challenging for the liquid biofuels. The first challenge occurs during ignition. The evaporation, and thus the ignition, will be challenging if the fuel is less volatile. If needed, this can be resolved by starting on another fuel to ensure a self-sustaining flame. Not all liquid fuels are suitable for operation across the full load range of the gas turbine, therefore requiring another fuel at part load conditions. In the OP16, this can be achieved by using bi-fuel or dual fuel operation. To combat this, the OP16 uses a pilot fuel (conventional high-calorific fuel) during the initial phase of operation for specific fuels. Once the gas turbine has reached an operating point where the bioliquid can sustain the combustion the pilot fuel can be switched off.

The liquid biofuels can contain a fair amount of carbon residue. The carbon residues are difficult to combust, but having extra residence time for the combustion can help to achieve this. If the carbon content is not burned out properly, it can start fouling the combustion liner, and result in shorter life time of the components. Since the 3C combustor of the OP16 gas turbine is significantly larger than conventional combustor, sufficient burnout time is provided and therefore higher levels of carbon residues can be allowed. Other contaminants, such as ash, salts and heavy metals, can attack the materials in the hot section if they start to condense. This will also result in shorter life time of the components. The robust all-radial design of the OP16 gas turbine is less sensitive for hot flow path damages and corrosion, as discussed in section 4.1.2.

Compared to gaseous biofuels, the liquid biofuels have the advantage that only a relatively small pump is required. The pump will have significantly less power consumption than the requirement for the gas compressor. This means when operating on liquid biofuels one will have the full benefit of the additional fuel mass flow (i.e. for low energy density fuels) and the electrical power will be higher compared to conventional fuels.

5 Biofuel pollutant emission regulation

The EU directive on the limitation of emissions of certain pollutants into the air from medium combustion plants is referred to as the MCP Directive. It lays down rules to control emissions of medium combustion plants and also a sets rules to monitor emissions of carbon monoxide (CO). The need to regulate CO, will be reviewed in 2023 (15). A medium combustion plant is an installation that has a rated thermal input equal to or greater than 1 MW and less than 50 MW. In case of local decentralized CHP plants, they will most likely fall under this definition. Within this directive there are a couple of exceptions, but the general cases are considered in this section which are split by existing and new plants. For new plants the directive will be active on the 20th of December 2018. Focusing on gas turbines, the emission limits are set for 70% load and above, and can be found in Table 1.For existing plants with a thermal input greater than 5 MW, the regulations are shown in Table 2 and become active from the 1st of January 2025. Existing plants with a thermal input equal or less than 5 MW need to comply to Table 2 from 1 January 2030. Existing machinery will most likely achieve a lifetime to be overhauled in the years towards the mid-2020s and retrofitting suitable combustion technology can be an option to meet regulations. The directive focuses on the emissions of NOx, SO2 and dust and this section will elaborate these emissions in relation to gas turbines.

The emission limits are applicable at 273.15 K, 101,3 kPa, dry and standardized 15 % O_2 content for engines and gas turbines on liquid and gaseous fuels.

Table 1: Emission limit values (mg/Nm3) for new engines and gas turbines (15)

Pollutant	*Type of medium combustion plant*	*Liquid fuels other than gas oil*	*Gaseous fuels other than natural gas*
SO_2	*Engine and gas turbine*	*120*	*15 (1)*
NO_x	*Gas turbines (2)*	*75 (3)*	*75*
Dust	*Engines and gas turbines*	10 *(4)*	-

(1) 40 mg/Nm^3 in the case of biogas.
(2) Emission limit values are only applicable above 70 % load.
(3) Until 1 January 2025, 550 mg/Nm^3 for plants which are part of SIS or MIS.
(4) 20 mg/Nm^3 in the case of plants with a total rated thermal input equal to or greater than 1 MW and less than or equal to 5 MW.

Table 2: Emission limit values (mg/Nm3) for existing engines and gas turbines (15)

Pollutant	*Type of medium combustion plant*	*Liquid fuels other than gas oil*	*Gaseous fuels other than natural gas*
SO_2	*Engine and gas turbine*	*120*	*15 (5)*
NO_x	*Gas turbines (6)*	*200*	*200*
Dust	*Engines and gas turbines*	*10 (7)*	-

(5) 60 mg/Nm^3 in case of biogas.
(6) Emission limit values are only applicable above 70 % load.
(7) 20 mg/Nm^3 in the case of plants with a rated thermal input equal to or greater than 1 MW and less than or equal to 20 MW.

Due to the low calorific value of most biofuels and the expected quality differences, there are some operational challenges. Flame stability due to the lower combustion temperatures and the difference in lean blow off limits require in some cases a high calorific pilot fuel to maintain a stable combustion process. A stable process is key and therefore the diffusion combustion process is favored over one of the main emission control technologies in gas turbines which uses a premixed flame. The latter is also known as the dry low NO_x (DLN) or dry low emissions (DLE) technology. This technology suppresses the thermal NO_x generation by reducing the peak flame temperatures. A diffusion flame is a result of fuel and oxidizer that are mixed by diffusion in the flame zone. The rate of mixing determines the combustion speed and the combustion zone is in general more compact and stable. A premixed flame, as the name suggests, makes use of premixed fuel and oxidizer which travel downstream to the combustion zone where it is ignited by the chemical reactions at place. Variations in fuel properties will influence a premixed flame more than the diffusion flame. An example of challenging fuel for DLN systems is syngas which can be derived from various (bio) feedstocks. The hydrogen in the syngas has a significant impact on the flame speed. This feature will increase the risk of flashback, which is a phenomenon were the flame travels upstream out of the dedicated combustion zone, damaging combustor parts.

Besides the operational challenges, controlling emissions seems to be not feasible by the current DLN technology. Considered from another angle, (ultra) low calorific fuels do have an advantage of having a low flame temperature. In a properly set-up system, NO_x emissions are expected to meet the new MCP directive, because the high amount of diluents suppress the creation of thermal NO_x. The OP16-3C combustion system showed promising results on various low LHV fuels by using purpose build diffusion flame combustion hardware (16). The clear challenge with low LHV fuels is that the fuel needs to have time to completely combust. A result of the lower flame temperature is a slower chemical reaction rate which could result in partly unconverted fuel. This will show immediately in the CO emissions and especially in case of liquid fuels, the possibility to emit unburned fuel fractions which form dust. The OP16-3C combustors are several volume sizes larger than conventional combustion hardware, to counteract the low LHV fuel properties. Figure 3 and Figure 4 show normalized results to a conventional diffusion combustor of representable syngas biofuels and the influence of LHV on the emissions of NO_x and CO. Higher LHV fuels tend to have in general, higher NO_x emissions if the combustor hardware is designed for the (ultra-) low LHV fuels. The OP16-3C design is purpose build to achieve low emissions for the lower ranges of LHV. On top of that, if the load percentage increases, the combustion zone increases in temperature. This has a direct effect on the NO_x values as function of temperature as well. Due to the larger combustor volume, CO emissions of the lower calorific fuels show a significant improvement over the conventional combustor hardware.

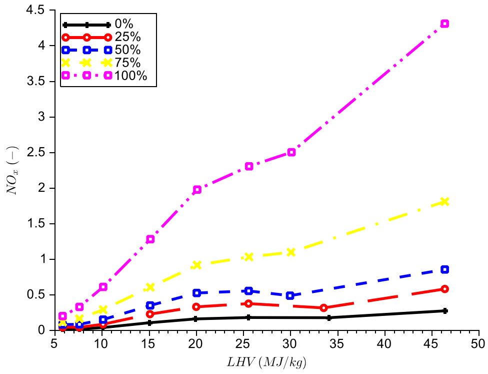

Figure 3: Syngas NOx emissions in relation to LHV. The curves represent different loads.

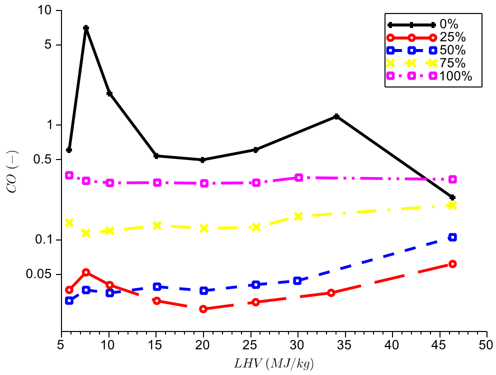

Figure 4: Syngas CO emissions in relation to LHV. The curves represent different loads.

In the case of bio liquids, not only the thermal NO_x affects total emissions. Fuels like pyrolysis oil often contain fuel bound nitrogen. If combustion of that fuel takes place, it will unavoidably convert the fuel bound nitrogen directly to NO_x. One can see in Figure 5 the effect of the nitrogen present in pyrolysis oil, compared to ethanol without fuel bound nitrogen and conventional diesel combusted in the OP16-3C combustor. Both ethanol and pyrolysis oil are low LHV fuels, but pyrolysis oil contained 0.1wt% of nitrogen content, resulting in higher NO_x emissions than for ethanol, despite the lower flame temperature. In Figure 6, the CO emissions of conventional diesel and the two bioliquids are shown. Above 70% load the ethanol resulted in comparable results to diesel, but the more challenging pyrolysis oil had several times higher CO values. The latter can be due to the more complex chemical composition and the challenges of atomization. The SO_2 emissions are like the fuel bound nitrogen emissions due to that all the elemental Sulphur that is in the gaseous or liquid fuel, will in general be converted to SO_2 in the exhaust stream. Conditioning the fuel to limit SO_2 emissions is of great importance, but adds additional costs to the process. In case of biogas production by fermentation, the H_2S contaminant is part of the natural biomass conversion process. Therefore, the MCP directive allows for higher SO_2 emissions in case biogas is used. Biomass digesters are also known to produce ammonia (NH_3) in some cases and when it is present and combusted, it will add to the plants NO_x emissions.

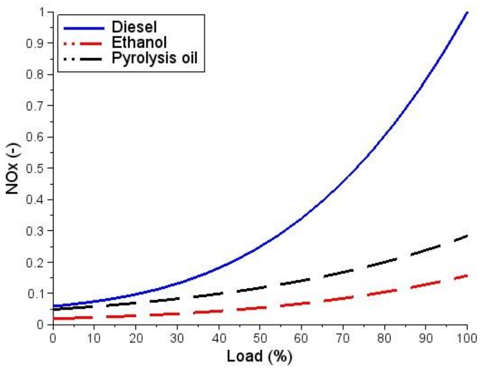

Figure 5: Liquid fuel NO_x emissions in relation to load

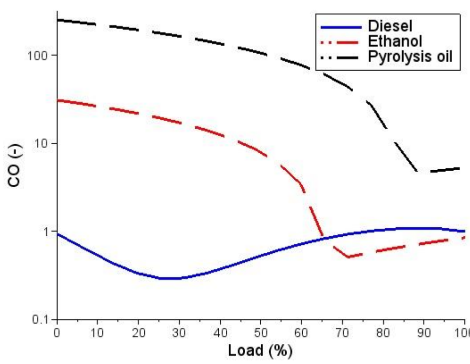

Figure 6: Liquid fuel CO emissions in relation to load

The final regulated emission type is dust. While combustion gaseous fuels, dust emissions are close to nonexistent and the values in the exhaust consist mainly of particles that came through the intake or due to engine materials. There is an exception while combusting biogas with siloxanes. If siloxanes are combusted silicon can, in combination with oxygen or other elements, form solid deposits and dust. Concentration of siloxanes are in general low, but they are expected increase because consumer product waste contains higher values as well. Dust emissions are regulated for liquid fuels and even if complete combustion takes place, it is expected that cleaning the exhaust flow in necessary. The quality of the oil is of great importance if one considers the particles and non-combustibles like ash. Dust emissions of biodiesel is in general lower than for conventional diesel fuels (17), but pyrolysis oil, due to the nature of the feedstock needs additional cleaning to ensure particulate and dust emissions are as low as possible (18). It is expected that pyrolysis oil will emit more than the MCP Directive permits for gas turbines and engines without additional measures. Overall, the results and the technical advantages of the OP16-3C design are promising in relation to the MCP directive. (Ultra-) low calorific biofuels can be utilized for the existing and new plants if they are in their gaseous form. The combustion hardware can be designed to have low emissions for a particular fuel, but it is important that the fuel properties such as LHV stays within a limited range. The sulphur content of the biogas will determine if the SO_2 values are met described in Table 1 and Table 2 and technical solutions exist to achieve clean fuels. For bio liquids, pyrolysis oils need to be of very good quality in relation to noncombustible parts and contain low fuel bound nitrogen. Still the MCP directive for new and existing plants will most likely not be met for dust and NO_x while combusting it in a gas turbine. Alcohols on the other hand are expected to meet the MCP directive in gas turbine applications.

6 Concluding remarks

The trend towards small-scale decentralized power generation has led to a growing interest to utilize fuels that are locally available. This trend, together with the wish to find alternatives for fossil fuels, has led to an increasing interest to operate gas turbines on biofuels. Biofuels differ significantly from conventional fossil fuels, as they have low energy density, different chemical composition and might contain unwanted contaminants. These aspects have a direct and significant impact on the gas turbine operation in terms of the combustion process, emissions and equipment life time. Therefore, it is important to carefully evaluate each fuel with respect to the OEM specifications. Smaller gas turbines are well-suited to handle the increasing demand for decentralized power generation in combination with utilization of unconventional fuels. The OP16 gas turbine, rated at 1.85 MWe, has a long track record from successful operation on challenging fuels. The unique all-radial design of the OP16 gas turbine makes it very suitable for operation on biofuels which are typically too difficult for other gas turbines and reciprocating engines. To meet the demand for utilizing biofuels OPRA has developed the OP16-3C configuration. The OP16-3C features a unique combustor technology, which enabes reliable and efficient operation on a wide range of liquid and gaseous biofuels including ethanol, pyrolysis oil and (ultra)-low calorific syngases.

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