Technical challenges and opportunities for utilizing syngas in gas turbines

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The trend towards small-scale decentralized power generation has led to a growing demand to utilize fuels that are locally available. This trend, together with the wish to find alternatives to the fossil fuels, has led to an increasing interest to operate gas turbines on (ultra) low-calorific fuels. Examples of such alternative fuels are syngas, waste gas and biogas.

This paper will review the technical challenges and possible solutions when operating single-shaft, constant speed, gas turbines on syngas. The composition of the syngas differs significantly from standard natural gas as it typically contains a large amount of hydrogen and carbon monoxide as well as a large fraction of dilutants. This has a direct and significant impact on the combustion process in terms of the flame stability and flammability limits. In addition, the added fuel flow, caused by the low energy density of the fuel, will increase the power output. However, it will also move the compressor operating point towards the surge limit. Several methods exist to address the decreasing surge margin and the paper will review some potential solutions. The discussion will be exemplified by cycle simulations from a generic single-shaft constant speed gas turbine.

The paper will be concluded with a presentation of the OP16-3C gas turbine. The OP16-3C gas turbine, rated at 1.85 MWe, has been developed to burn (ultra) low-calorific fuels. It is an all-radial single-shaft gas turbine based on the well-proven OP16 gas turbine configuration. The OP16-3C features a new combustion chamber, which has successfully burned a syngas with an LHV as low as 6 MJ/kg.

1. Introduction

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 to the fossil fuels, has led to an increasing interest to operate gas turbines on (ultra) low-calorific fuels. Examples of such alternative fuels are syngas, waste gas and biogas. However, the properties of these fuels make them challenging.

Figure 1 shows an overview of different gaseous fuels suitable for gas turbines. Syngas, or synthetic gas, is one of the (ultra) low calorific gases and is a general name for a gas with carbon monoxide and hydrogen. Syngas can be made from coal and natural gas as well as from several renewable resources such as wood and waste. The composition of syngas differs significantly from standard natural gas as it typically has a low content of hydrocarbons and instead contains a large amount of hydrogen and carbon monoxide as well as a large amount of dilutants. This has a direct and significant impact on the combustion process in terms of the flame stability and the flammability limits. In addition, the added fuel flow caused by the low energy density of the fuel will increase the power output. However, it will also move the operating line towards the surge line.

Table 1 provides a comparison between five selected syngas fuels (SG1-SG5) and one natural gas (NG). As the heating value decreases the amount of hydrocarbons in the fuel, such as methane, decreases. At the same time the dilutants, such as carbon monoxide and nitrogen, increases.

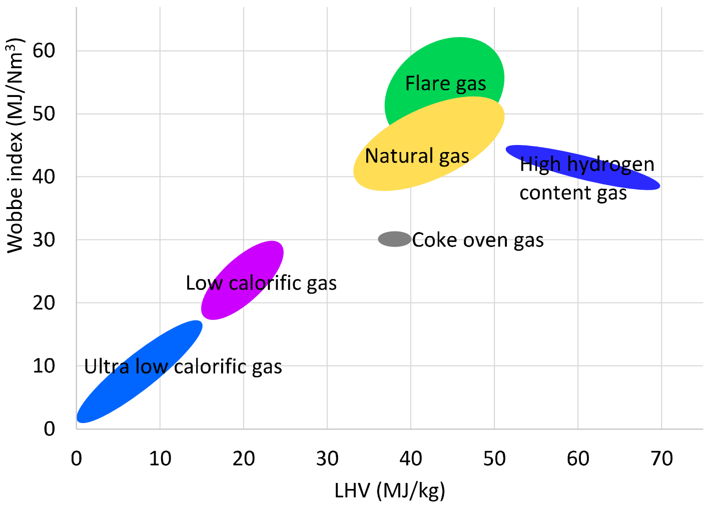

Figure 1. Overview of different gas turbine gaseous fuels.

Table 1. Comparison between different syngas fuels and natural gas.

	SG1	SG2	SG3	SG4	SG5	NG
Hydrocarbons (%)	5.0	16.3	24.4	32.6	40.7	98.9
Hydrogen (%)	16	18.7	21.8	22.9	24.6	0.0
Carbon monoxide (%)	22	18.7	21.8	22.9	24.6	0.0
Nitrogen (%)	46	36.0	23.9	16.0	1.1	0.4
Carbon dioxide (%)	11	10.4	8.0	5.7	9.1	0.7
LHV (Btu/scft)	160	260	352	433	517	931
LHV (MJ/kg)	5.6	10.0	15.0	20.0	25.0	48.0

2. Syngas as a fuel for gas turbines

Syngas is a challenging fuel for gas turbine operations. Not only the combustion process is affected but also the operational aspects of the gas turbine are affected. However, there are also additional benefits of using syngas compared to conventional high-calorific fuels. This section will describe the most important aspects of syngas operation starting with the combustion process.

2.1. Combustion process

The combustion process can be explained as an exothermic reaction of a fuel and an oxidant. The fuel can be both liquid and gaseous and the variation is large as was discussed earlier. However, the oxidant is always air for gas turbine applications. In gas turbine applications the combustion process is self-sustaining, i.e., once it has been ignited it will continue the burning process by itself as long as the right conditions are fulfilled. The flames can be divided into two different categories: pre-mixed flame or diffusion flame. Pre-mixed flames are characterized by the fact that the air and fuel is mixed before the combustion process takes place, while the diffusion flames are characterized by that the air and fuel are mixed in the flame by diffusion.

Independent on the flame type the combustion process needs to take place within a certain time, given by the volume of the combustion chamber. The reaction time of the process is strongly dependent on the fuel composition. The combustion of syngas differs from the natural gas in several aspects. The lower heating value of the syngas fuels leads typically to a low flame temperature and as a result the reaction rates are decreased. In addition, the hydrogen and carbon monoxide in the fuel affects the reaction rates significantly. Hydrogen reacts fast while carbon monoxide reacts slowly. The above is illustrated in Figure 2, where the required residence time as a function of the lower heating value is shown. The residence time is a measure of the time required to completely combust the fuel. The graph shows the residence times relative to the residence time for natural gas and they are a measure of the time required to completely combust the fuel. The required residence time is increasing as the LHV decreases, and towards the lower end the residence time increases rapidly.

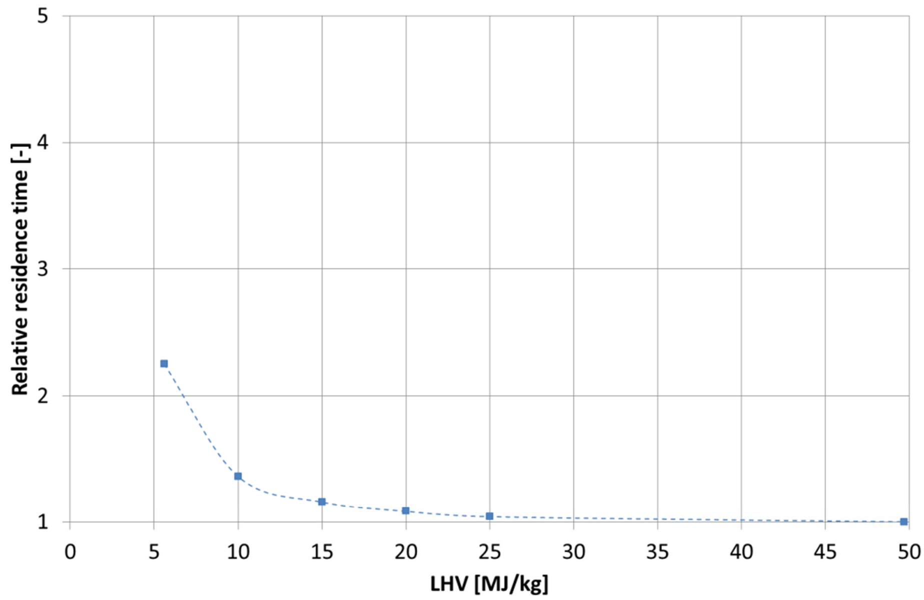

Figure 2. Relative residence required for complete combustion as a function of the LHV.

Another important aspect for the combustion of syngas is the flammability limits. Not all air and fuel mixtures will burn and/or explode. The lowest fuel-to-air ratio that is flammable is referred to as the lower flammability limit or blowout limit. As the fuel-to-air ratio increases the upper flammability limit, or rich limit, might eventually be reached. However, for the application of low-calorific fuels we are mainly interested in the lower flammability limit. The lower flammability limit is important since it defines if and when a pilot fuel is required. For some low-calorific fuels no pilot fuel is required whereas for other low-calorific fuels a pilot fuel is required for start-up and/or up to a certain load. The lower flammability limit can be defined using the equivalence ratio, see equation 1.

$$\emptyset_{bo} = \frac{blowout\ fuel\text{−}to\text{−}air\ ratio}{stoichiometric\ fuel\text{−}to\text{−}air\ ratio} = \frac{\left(m_{fuel}/m_{air}\right)_{bo}}{\left(m_{fuel}/m_{air}\right)_{st}} \qquad \textit{Eq. 1}$$

The equivalence ratio describes the fuel-to-air ratio referenced to the stoichiometric fuel-to-air ratio. The stoichiometric fuel-to-air ratio is the ratio where the air is exactly enough to completely burn all the fuel. The equivalence ratio for the blowout limit, $ø_{bo}$, is a measure of the fuel-to-air ratio the mixture is too lean to be flammable. The composition of the fuel has a strong influence on the blowout limit. Figure 3 shows the lower flammability level for two different categories of fuels as a function of the lower heating value. The blowout limits have been made non-dimensional using the blowout limit for natural gas as the reference fuel. The red line is representing the syngas fuels and the blue line represents hydrocarbon based fuels. The behavior for the two fuel types is very different when the lower heating value is decreasing. The lower flammability limit for the hydrocarbon based fuels shift towards a higher equivalence ratio when the energy content in the fuel decreases.

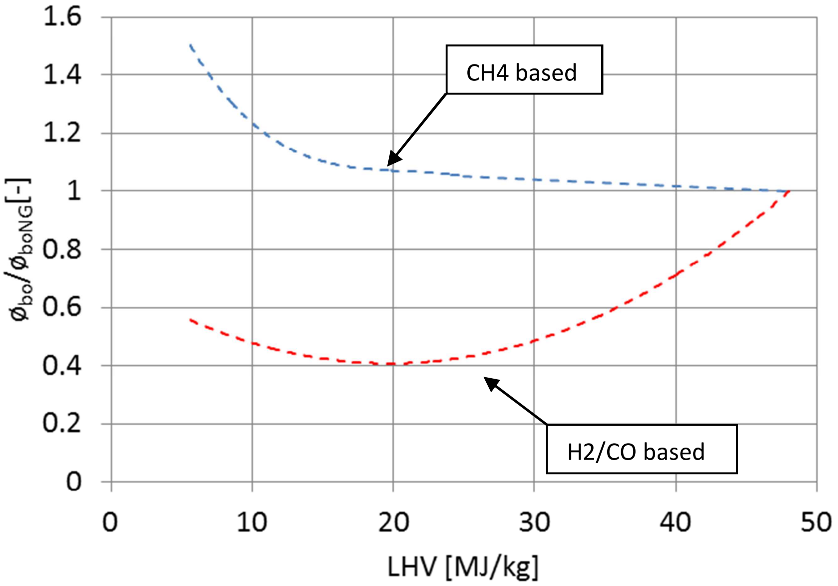

Figure 3. Equivalence ratio for the lower flammability limit referenced to natural gas.

This means that for fuels with low energy content the blowout will occur at lower fuel-to-air ratios. However, for the syngas fuels the equivalence ratio for the blowout limit is generally lower than for natural gas. This behavior is caused by the hydrogen contained in the syngas fuels.

For single-shaft constant speed gas turbines the lower flammability limit is important. This is because the mass flow is more or less constant across the load range for these types of machines, meaning that the fuel-to-air ratio decreases at part-load operation. Therefore, fuels containing hydrogen (e.g. syngas) will allow operation at part-load without the need for a pilot fuel, while for hydrocarbon based fuels a pilot fuel might be required during part-load operation as the heating value decreases.

2.2. Gas turbine performance

Syngas has typically a significantly lower energy density than natural gas, which requires a higher fuel mass flow of syngas to reach the desired combustor exit temperature. If one considers the gas turbine as an isolated system with the thermodynamic boundary at the fuel nozzle inlet, the added fuel mass flow leads to an increase of the power output and a decrease of the heat rate. Since the amount of syngas entering the combustor is significantly larger than for natural gas this added mass flow will increase the power output since it will not be compressed by the gas turbine compressor. Also, the total heat input from the fuel remains approximately the same and therefore the heat rate will decrease.

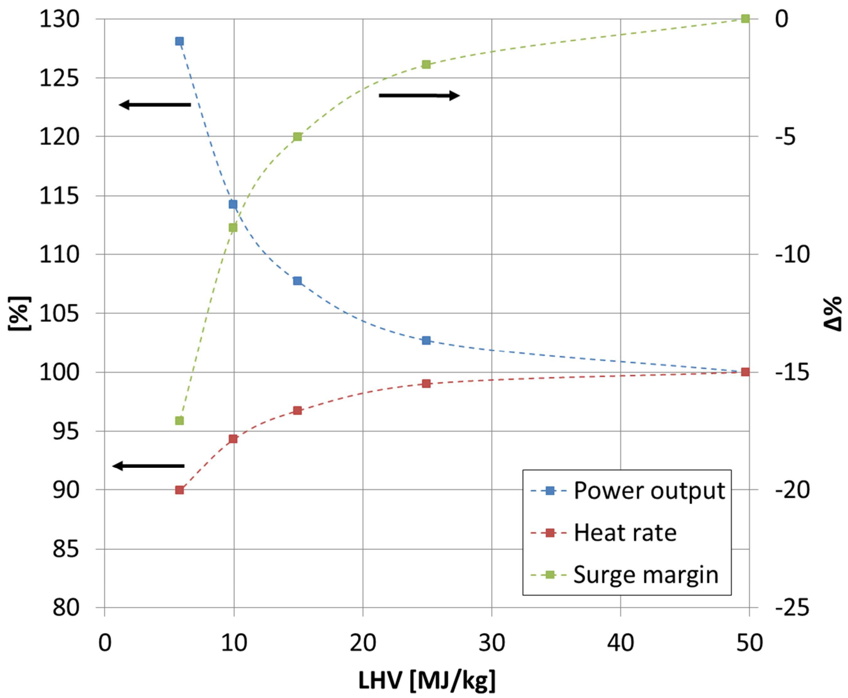

Figure 4. Effect of the LHV on the power, heat rate and surge margin for a generic single-shaft gas turbine.

The effect of the lower heating value on the power output, heat rate and surge margin for a generic single-shaft gas turbine is illustrated in Figure 4. This graph shows calculations for four different syngas fuels with a lower heating value between 6-25 MJ/kg and one natural gas fuel with a lower heating value of 49 MJ/kg. Decreasing the heating value to about half has only minor effect on the power and heat rate. The surge margin is only decreasing with a few percentage points and this can typically be handled by most gas turbines without the need to adjust the operating point or hardware. However, as the heating value decreases further the power output increases exponentially with almost a 30% power increase for a heating value of 6 MJ/kg. However, this significantly decreases the surge margin and such a decrease cannot be accepted without modifications to the engine hardware or the operating point. The decreasing surge margin and ways to combat this will be discussed in the following section.

2.3. Compressor surge

As mentioned in the previous section, the benefit of improved simple cycle performance comes with a drawback: Increased risk for compressor surge. Surge is the point at which the compressor cannot add enough energy to overcome the back pressure. The first stage nozzle guide vanes of the turbine are typically choked during normal operation. This means that the flow reaches a Mach number of unity. Contrary to popular believe this does not mean that the mass flow is restricted to increase further but rather the velocity. The mass flow can be increased but this requires the pressure to increase, which in a turbine implies that the compressor discharge pressure will also increase.

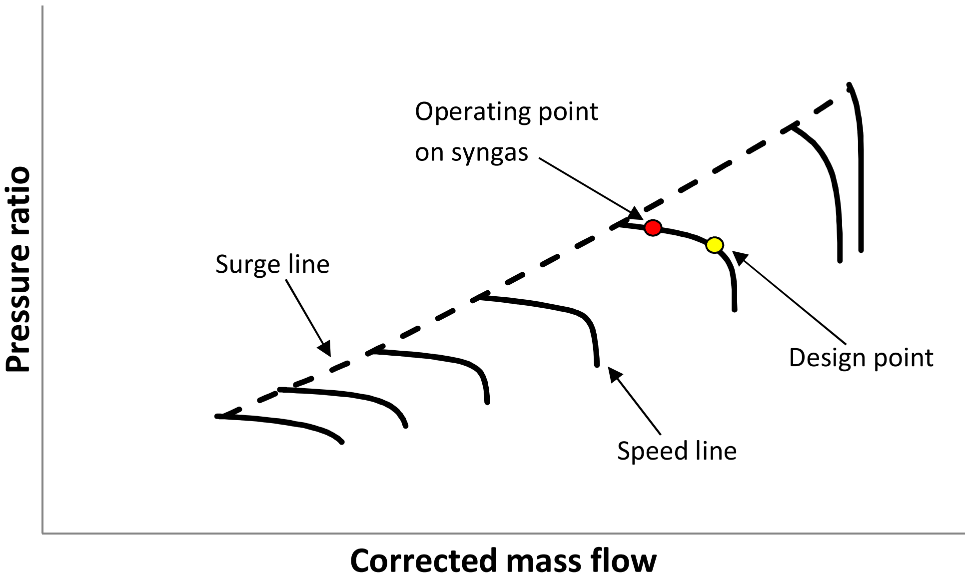

Figure 5. Generic compressor map.

As the compressor backpressure increases further it will reach a condition where the compressor operation can no longer be sustained and the compressor might get into surge. Compressor surge is characterized by a pulsating flow and increasing vibrations and it might eventually lead to a catastrophic failure of the gas turbine. Figure 5 shows a generic compressor map. The vertical axis shows the pressure ratio while the horizontal axis shows the corrected mass flow. The solid line is the non-dimensional speed lines and the dashed line is the surge line. For a given speed line the mass flow increases when the pressure ratio decreases. Once the compressor is choked the pressure ratio (and efficiency) tends to decrease rapidly while the mass flow remains nearly constant. Assume that the yellow marker in the graph above is representing the design point when operating on natural gas. If, for a single-shaft constant speed machine, the heating value is decreasing the operating point will be shifted towards the red marker. Hence, the distance to the surge line is much smaller and any further decrease in heating value will eventually drive the compressor into surge.

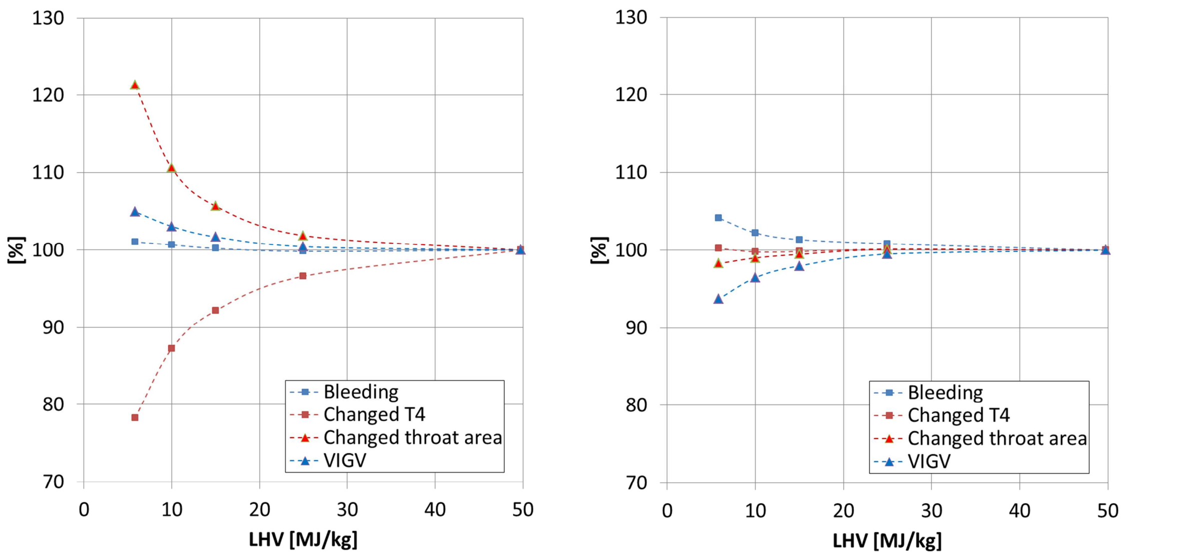

Figure 6. Comparison of different methods to increase the surge margin. Left: Power output. Right: Heat rate.

Therefore, it is of great importance to adjust the situation when operating on syngas and other fuels with low energy density. Several methods exist to combat the surge issue. The most common ones are:

- Variable inlet guide vanes (VIGV)
- De-rating to operate with a lower combustion exit temperature (T4)
- Compressor air bleeding
- Increased turbine throat area

Each of the methods has its advantages and disadvantages. Figure 6 shows a quantitatively comparison between the four different methods using same generic single-shaft gas turbine as above. For all calculations the surge margin has been kept the same as for the case when operating on natural gas. All methods except the decreased combustor exit temperature provide an increase in the power output. However, the increased throat area provides significantly larger power increase than when using compressor bleed and variable inlet guide vanes. As can be seen from the graph the variable inlet guide vanes and increased throat area both decrease the heat rate, i.e. provides higher cycle efficiency. The other two methods increase the heat rate. Based on these calculations the variable inlet guide vanes and increased throat area are both superior to the other two methods. However, one should keep in mind that most often the syngas needs to be compressed prior to entering the fuel nozzles. The gas compressor used for boosting the syngas pressure will consume more power since the fuel flow is higher. Hence, the increased throat area seems to be the most beneficial as it provides the highest power output which is needed in order to compensate for the larger gas compressor power demand. The above only takes into consideration of the thermodynamic cycle and other factors, such as the gas turbine configuration, will also influence the choice of method.

3. The OP16-3C gas turbine

OPRA Turbines develops, manufacturers, markets and maintains gas turbine generator sets. The generator sets are powered by the robust and efficient OP16 gas turbine, which is rated at 1.85 MWe. The generator package is a containerized solution that includes the OP16 gas turbine, fuel systems, generator, control system, air intake and ventilation system. The generator sets can be provided in a variety of configurations to meet specific customer requirements. These sets can be installed as single or multiple units, covering installation requirements from 1.5 to 10 MW. The OPRA OP16 is a single-shaft all-radial gas turbine for industrial, commercial, marine and oil and gas applications. Since its market introduction in 2005 more than 80 generator sets based on the OP16 gas turbine have been delivered worldwide and the OP16 has accumulated more than 1.5 million operating hours. The main markets are onshore and offshore oil and gas applications as well as industrial and commercial CHP applications.

To meet the growing demand to utilize low-calorific fuels, such as syngas, OPRA Turbines introduced the OP16-3C gas turbine in 2014. The OP16-3C, shown in Figure 7, complements OPRA's OP16-3A (conventional combustor) and OP16-3B (DLE combustor) gas turbines by extending the fuel flexibility to include (ultra) low-calorific fuels. The OP16-3C gas turbine features a new combustion chamber (patent pending, Beran *et al* [1]), which has been developed to handle (ultra) low calorific liquid and gaseous fuels efficiently. The range of fuels includes, but not limited to, syngas, biogas, waste gas, coal-derived gas, pyrolysis oil and ethanol. The 3C combustor is designed to cover LHV's between 10-25 MJ/kg, but even lower LHV's can be acceptable depending on the fuel composition. Higher LHV fuels, such as diesel and natural gas, can also be burned in this combustor but then it is primarily used as a back-up fuel.

The OP16-3C utilizes the same engine core as the OP16-3A and OP16-3B gas turbines. It features a single stage centrifugal compressor with a nominal pressure ratio of 6.7:1. This moderate pressure ratio reduces the need for gas compression prior to introducing the fuel into the gas turbine. The radial turbine wheel, which is mounted back-to back with the compressor, has been aerodynamically optimized to achieve a high efficiency. The compact compressor/turbine configuration permits the use of an overhung rotor assembly where the bearings are located on the cold side only. The all-radial configuration makes it a robust design and insensitive to foreign object damages and fuel contaminants. The combustion system consists of four can combustors mounted in a reverse flow direction. This is convenient for the maintenance as well as to provide uniform temperature and flow distribution into the turbine.

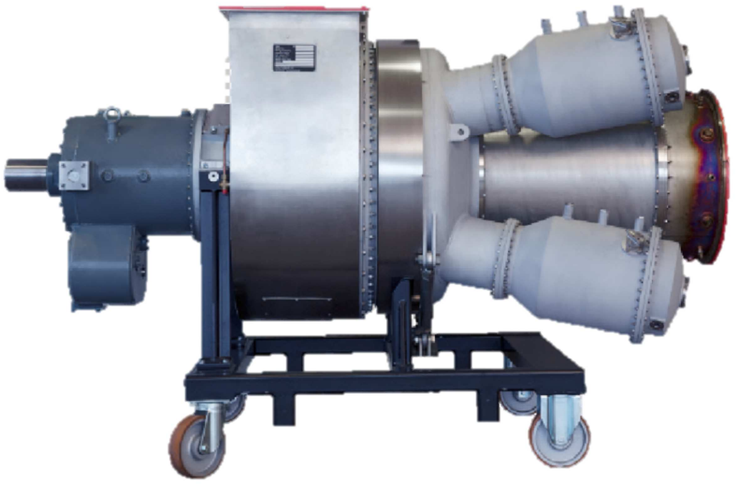

Figure 7. The OP16-3C gas turbine.

As discussed in previous sections the low-calorific fuels require a longer time to complete the combustion process. To address this, the combustor volume of the OP16-3C is significantly larger than for the conventional combustion systems. This ensures sufficient time for complete combustion of the carbon monoxide in the syngas. The increase of the combustor volume can be achieved relatively easy in the OP16 gas turbine due to the reverse-flow mounting of the can combustors; hence, the overall footprint of the gas turbine remains the same and it fits into the standard OP16 package assembly.

The OP16-3C combustor has been successfully tested on a wide range of syngas fuels including a syngas with an LHV as low as 6 MJ/kg. The OP16-3C is equally well suited to handle other (ultra) low-calorific liquid and gaseous fuels including biogas, waste gas, coal-derived gas, pyrolysis oil and ethanol. More details about the application of pyrolysis oil and ethanol in the OP16-3C can be found in Beran and Axelsson [2].

The OP16-3C, as well as the OP16-3A and OP16-3B, can be equipped with a dual fuel nozzle to operate on both gaseous and liquid fuels. This enables the OP16 gas turbine to operate in dual fuel mode and/or bi-fuel mode. Dual fuel means that the gas turbine can switch from one fuel to another whereas bi-fuel operation is a continuous combustion of two different fuels at the same time. The OP16 control system has been designed to ensure that the gas turbine can switch from one fuel to another during engine operation including full load. The application of dual and bi-fuel operation is essential for operation on syngas. For example, some times the supply of the syngas is not always sufficient due to fluctuations in the available feedstock. Then, another fuel can be used as a back-up fuel. In addition, not all syngas fuels can be used in the whole load range of a gas turbine as was discussed in the previous sections. For these cases the bi-fuel operation can be employed to boost an ultra lean fuel during the start-up and part-load operation till 100% syngas can be used.

The decreased compressor surge margin is easily handled in the OP16-3C by operating with a larger turbine throat area. This method is the preferred choice as it provides the highest power output and also a reduction in the heat rate without the need to apply variable inlet guide vanes.

4. Conclusions

The trend towards a more decentralized power market has increased the interest for smaller gas turbines. Also, this trend opens up for utilization of fuels that are locally available. A wide range of potential non-conventional fuels exists and one of the more interesting alternatives is syngas. Since the physical and chemical properties of syngas fuels are significantly different compared to natural gas it requires new combustion technology. This is because the reaction rate of the syngas is lower and therefore requires more time for complete combustion. In addition to the combustion process, the syngas is also changing the performance and operability of the gas turbines. For single-shaft gas turbines the added mass flow drives the compressor towards it surge line and methods to prevent this must be employed. In this paper several alternatives have been discussed and the two most suitable methods are the use of variable inlet guide vanes or increase of the turbine throat area. The latter provides a significant increase in the power output and a decrease in the heat rate while maintaining the surge margin.

To meet the demand to utilize syngas and other (ultra) low-calorific fuels OPRA Turbines introduced the OP16-3C gas turbine in 2014. The OP16-3C is based on the all-radial OP16 gas turbine configuration but features new and advanced combustion technology. The new combustor is able to burn gaseous and liquid fuels with as low heating value as 10 MJ/kg and under certain conditions even lower values can be accepted. The OP16-3C gas turbine expands OPRA's markets and applications as it can burn biogas, syngas, waste gas, coal-derived gas, pyrolysis oil and ethanol.

References

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[2] Beran, M. and Axelsson, L.-U., "Development and Experimental Investigation of a Tubular Combustor for Pyrolysis Oil Burning," in *Proceedings of ASME Turbo Expo 2014*, Düsseldorf, Germany, 2014.