Operational experience of the OP16 gas turbine in small scale CHP installations in Europe

Lars-Uno Axelsson, Ruud van Groenewoud and Mark Stulp

OPRA Turbines, the Netherlands

The trend towards more decentralized power generation in Europe has made small gas turbines an attractive complement to the large power plants. This trend, together with the increasing amount of renewable power feeding the grids, has led to additional challenges for the traditional power generation equipment. This includes more part-load operation, weaker electric grids, changing fuel compositions and new fuel sources. While facing these challenges the end users still need to meet the stricter emission limits and the requirement for high efficiency. In order to promote the development of energy efficient power solutions, certain countries within the European Union have implemented subsidy schemes. Such schemes have been proven to help smaller and medium sized industries to transit to more efficient and environmentally friendly power production by using combined heat and power solutions.

This paper will discuss the operational experience of the OP16 gas turbine, rated at 1.85 MWe, for combined heat and power (CHP) applications in Europe. Case studies representing different CHP applications will be presented. The operational experience will be discussed using data obtained from the field.

1. Introduction

Combined heat and power (CHP) or cogeneration is the simultaneous generation of useful thermal and electrical/mechanical energy from one prime mover. The prime mover is typically a gas turbine or a reciprocating engine. By utilizing both the mechanical/electrical energy and the thermal energy high overall fuel utilization can be achieved. Depending on the prime mover and application the overall fuel efficiency can be between 70-90%. The exhaust heat can be used in many different ways including:

- Direct drying in industrial applications
- Steam generation for industrial applications
- District heating and cooling
- Electrical energy using (organic) Rankine cycles

The power generated by CHP installations has steadily increased in Europe from the early 90's up to today. Although Europe has a relatively large portion of CHP installations there is a huge variation between the countries. Today, about 20% of the total installed capacity of the conventional power plants in Europe is based on CHP [1]. However, only 11 of the 28 countries included in this statistics makes up for more than 85% of the total CHP capacity.

During the recent years small gas turbines have gained increasing popularity in CHP applications for small and medium size industrial applications. This trend, together with the increasing amount of renewable power feeding the grids, has led to additional challenges for the traditional power generation equipment. This includes more part-load operation, weaker electric grids, changing fuel compositions and new fuel sources. While facing these challenges the end users still need to meet the stricter emission limits and the requirement for high efficiency. In order to promote the development of energy efficient power solutions, certain countries within the European Union (e.g. Germany) have implemented subsidy schemes for "high efficiency" CHP installation. Such schemes have been proven to help smaller and medium sized industries to transit to more efficient and environmentally friendly power production by using combined heat and power solutions.

This paper will discuss the application and operational experience of the OP16 gas turbine in CHP applications in Europe. The case studies will demonstrate how smaller industries can benefit from using gas turbines. The discussion will be exemplified using data obtained from the field.

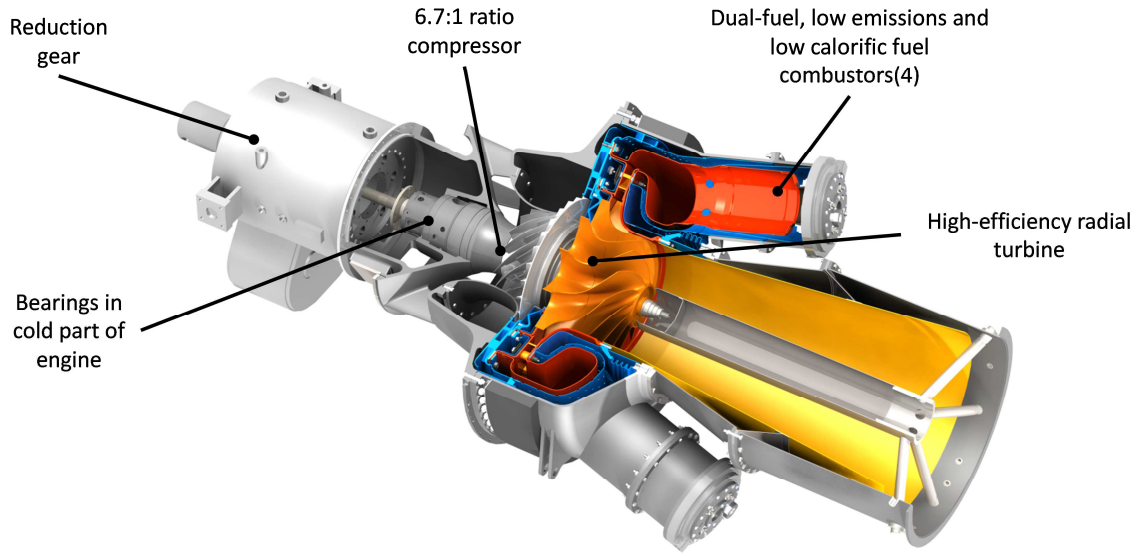

Figure 1. The OP16 gas turbine

2. The OP16 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 (Figure 1) is a single-shaft all-radial gas turbine for industrial, commercial, marine and oil & gas applications. Since its market introduction in 2005 many generator sets based on the OP16 gas turbine have been delivered worldwide and the fleet has accumulated more than 1.5 million operating hours. The OP16 gas turbine features a single stage centrifugal compressor with a nominal pressure ratio of 6.7:1. The 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 the OP16 robust 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.

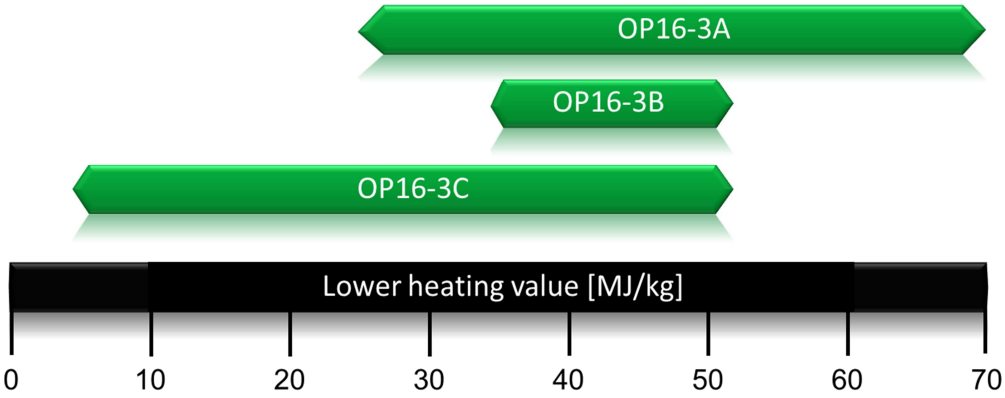

Figure 2. The lower heating value range (indication) for the OP16 product line.

The OP16 product line consists of three different configurations. The different configurations all have the same engine core and differ only by the combustion system. The OP16-3A has a conventional combustor operating with a diffusion flame. It was introduced in 2005 and can handle a wide range of gaseous fuels including natural gas, biogas, hydrogen rich gas and syngas. The OP16-3A has dual-fuel capability and can operate on both liquid and gaseous fuels including switch-over at full load operation. The OP16-3B configuration was introduced in 2007 to meet the more stringent emission requirements in Europe and other locations. It features a low-emission combustor operating with a lean pre-mixed flame. Although it is intended for natural gas operation it can also operate on liquid fuel as a back-up fuel (diffusion flame). The third configuration is the OP16-3C, which was introduced in 2014. This configuration has been developed to meet the increasing demand to utilize (ultra) low-calorific gaseous and liquid fuels including waste gas, syngas, biogas, ethanol and pyrolysis oil. A summary of the typical lower heating value range for the different configurations are provided in Figure 2. For more information about the operation on alternative fuels and the fuel flexibility capabilities of the OP16 the reader is referred to *Axelsson and Beran* [2], *Beran and Axelsson* [3] and *Bouten et.al.* [4].

3. The OP16 for CHP applications

The OP16 gen-set consist of two 20-feet containers (Figure 3). The lower module houses the gas turbine and generator as well as the auxiliary equipment including oil system, electro-hydraulic starting system, gas and/or liquid fuel system. The upper module is the filtration and ventilation module. The gas turbine gen-set has been designed in a modular way to enable easy and fast configuration of the product based on the customer requirements. This is essential in order to minimize the lead time as well as the commissioning time on site. The complete gas turbine train and associated equipment mounted on the skid are protected by a weatherproof, insulated and sound attenuated enclosure. The doors on the enclosure walls are designed to enable easy access to all equipment in the enclosure and to enable removal of the engine and generator from either side of the package. The weatherproof ventilation and air intake system is directly mounted on the top of the main enclosure.

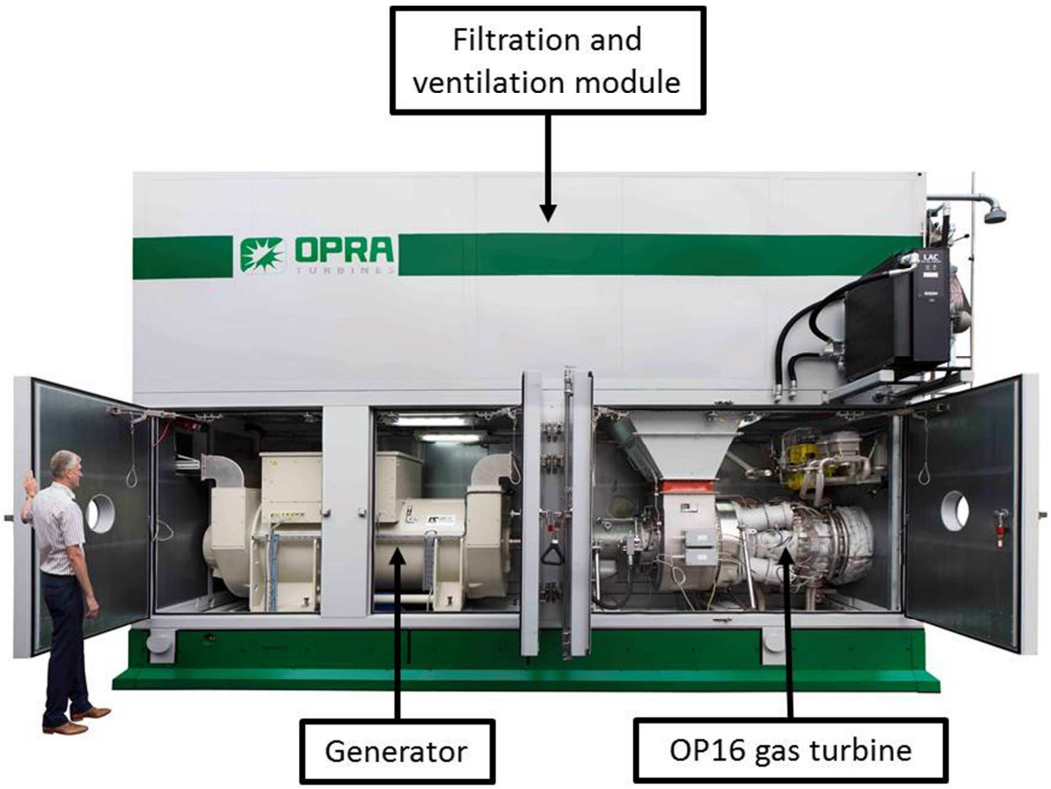

Figure 3. The OP16 modular package.

The OP16 gen-set have certain features making it well-suited for the demand from the market for increased flexibility. The simple and robust all-radial configuration permits fast start-up of the unit as well as the possibility to handle large load steps and load sheds. The capability to handle large load sheds is becoming increasingly important as the electric grids are becoming weaker and grid failures are more likely to occur. However, if there is a grid failure and the breaker opens the OP16 gas turbine control system will ensure that the engine will be brought down to idle operation and the operator can synchronise the unit and be back online very shortly. Furthermore, by having the bearings located only in the cold section there is virtually no lube oil consumption. An additional benefit of having the bearings in the cold section is that the exhaust is free of oil, which might not be the case if bearings are located in the hot section as the oil might leak into the exhaust. Having a clean exhaust is very important for CHP application where the heat is used for food processing applications.

To reduce the commissioning time on site it is important to be able to test as much as possible of the unit before shipment. In order to address this, OPRA has invested in test facilities to be able to test the complete gen-set prior to shipment. This test cycle includes I/O checking, control system functionality and load testing.

4. Example of CHP applications in Europe

This section provides examples of different CHP installations using the OP16 gas turbine. As will be seen, the applications are different but the common goal is to achieve high reliability, high efficiency and to meet the stricter emission regulations.

4.1. Starch manufacturing plant

In 2012 OPRA Turbines installed the first gen-set in Germany for a CHP application. The client, a wheat starch manufacturer, is one of Europe's leading companies in this sector (Figure 4). Initially starch was produced from potatoes for the food industry, but this was later switched to wheat. With the development and enhancements in process technology, new applications for wheat starch and its by-products were initiated. In the early eighties, the client began specializing in adhesives for the corrugated board and paper industries. Through innovation and process efficiency the client has developed an extensive range of products and has grown to become one of Europe's leading companies within this sector. The client has long experience from operation of gas turbines and has several installed for supplying heat and power to their plant.

The manufacturing of wheat starch requires large quantities of clean and high temperature exhaust gas. The exhaust heat will be utilized for direct drying for the starch production and preparing the starch for the subsequent production processes. Existing gas turbines installed several years ago did not comply with the new German air emission regulations (Technische Anleitung zur Reinhaltung der Luft and is commonly referred to as TA Luft).

To fulfil the regulations and the plant's energy demand, the client chose to replace existing units with an OP16-3B gen-set.

Figure 4. One OP16-3B gen-set installed at a starch manufacturing plant in Germany.

With an exhaust gas temperature of 575^{0}C and a mass flow of 8.7 kg/s, the OP16-3B is ideal for this application. The high temperature exhaust gas provides some 4.5 MW thermal energy in addition to the 1.8 MW electric power. The electricity produced by the gen-set is supplied to the grid. The factory is operating 24/7 and as a result, the turbine is operating almost continuously on full load. For this application it is important to have no oil residues in the exhaust gas. Hence, as discussed in previous section the all-radial configuration of the OP16 is well-suited for these application as the bearings are only located in the cold section of the engine.

4.2. Tobacco manufacturer in Germany

Another CHP application where the OP16 gas turbine is utilized is in a tobacco factory in Germany. This factory has a long history of operating gas turbines to generate steam and power for their plant. The steam generated is typically used for drying the tobacco. At this site one OP16-3B gas turbine is installed to provide about 1.7 MW electric power. In addition, the gas turbine is connected to a parallel fired waste heat recovery steam boiler (WHRSB). The exhaust heat from the gas turbine produces about 6.5 tons of steam per hour with a pressure of some 10 bar. By utilizing a parallel fired WHRSB a total steam production of 14.5 tons per hour is achieved.

4.2.1. Primary energy savings (PES)

Germany has implemented subsidy schemes to promote the use of CHP. By qualifying as a "high efficiency" CHP installation the end-user will get economic benefits. To quantify and qualify a CHP installation the so called primary energy savings need to be determined (eq. 1).

$$\text{PES} = \left(1 - \frac{1}{\frac{\text{CHP H}\eta}{\text{Ref H}\eta} + \frac{\text{CHP E}\eta}{\text{Ref E}\eta}}\right) \text{x } 100\ \% \qquad \text{Eq. 1}$$

where CHP Hη is the heat efficiency from the cogeneration production defined as the annual useful heat output divided by the fuel input used to produce the sum of the useful heat output and electricity from the cogeneration. Ref Hη is the efficiency reference value for separate heat production. CHP Eη is the electrical efficiency of the cogeneration production defined as the annual electricity from the cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from the cogeneration. Ref Eη is the efficiency reference value for separate electricity production. In addition, certain correction factors for the grid losses and different ambient conditions will apply to the above equation. However, the essential meaning of the PES is to determine how much more efficient a certain CHP installation is compared to producing the power and heat/steam separately. In order for an installation to qualify as a "high efficiency" CHP installation the PES shall be higher than 10%. To qualify as a high efficiency CHP installation the performance must be measured and evaluated by an accredited party. For this installation TÜV SÜD was enrolled. The measured data showed a PES of more than 16%. Hence, the installation was meeting the criteria for high efficiency CHP installation with a large margin and it was approved by TÜV SÜD.

4.2.2. Safety requirements

In addition, there are certain additional safety requirements when operating a gas turbine in combination with a boiler. TÜV SÜD was also responsible approve the installation according to the overall safety regulations. One of the key aspects is to ensure quick shut-off of the fuel supply in case of a flame out, which typically needs to be faster than when operating without a boiler. This is to avoid unburned fuel reaches the high temperature regions of the boiler and ignites. To comply with the German regulations the flame detection requires a safety integrated level (SIL) of 3. To ensure this, OPRA has developed the option to install an optical flame monitoring system in addition to the existing thermocouple-based flame monitoring system. This system is certified by TÜV SÜD and is having a SIL rating of 3. The installation including the OP16-3B gas turbine was determined to meet all the required regulations for safe operation and was certified accordingly.

5. Operational experience from CHP applications in Europe

This section will discuss the operational experience from the CHP applications in Europe. First the combustion system will be discussed followed by the gas turbine rotor module.

5.1. Combustion system and emissions

Although there is a process towards harmonization of the emission regulations, the requirements vary between the different European countries. Today, Germany is one of the countries with the strictest regulations. Their air pollution regulation restricts emissions of oxides of nitrogen, carbon monoxide and sulphur dioxide to mention the ones most applicable for gas turbines operating on natural gas. The formation of oxides of nitrogen is due to four mechanisms: thermal nitric oxide, nitrous oxide mechanism, prompt nitric oxide and fuel nitric oxide (Lefebvre and Ballal [5]). The basic objectives for low-emission combustion systems in order to reduce the NOx emissions are to lower the flame temperature, eliminate hot spots and minimize the time available to produce nitric oxides. Carbon monoxide (CO) emissions represent incomplete combustion of the fuel. The typical source of CO is due to low fuel-to-air ratio and/or too short residence resulting in too low burning rates. In addition, the mixing of the fuel and air is important in order to avoid local lean regions in the combustion region. Furthermore, the introduction of flame tube cooling air will quench the flame and hence it will stop the combustion process and produce CO due to incomplete combustion. As discussed previously, the OP16-3B gas turbine features a dry low-emission combustion system. The air and fuel is mixed prior to combustion and it operates in with a lean flame. The flame is stabilized using a radial swirler. To ensure stable operation during start-up and at part-load a pilot flame is used. To avoid quenching of the flame, impingement cooling of the flame tube (liner) is used instead of film cooling. The combustion system has been designed for robust operation independent on the natural gas composition.

Table 1. Different natural gas compositions.

	Unit	Type L	Type H
CH4	% (mol)	84.5	96.5
C2H6	% (mol)	1.7	1.6
C3H8	% (mol)	0.2	0.5
C3+	% (mol)	0.1	0.1
N2	% (mol)	11.8	1.0
CO2	% (mol)	1.8	0.3
LHV	MJ/kg	38.7	48.7
LHV	MJ/Nm^3	31.6	36.1

In Europe the natural gas composition is varying depending on the location. Even within a single country, e.g. Germany, the variation in fuel composition is large. The natural gas for the applications above operates with different natural gas composition as shown in Table 1. Type L is lower quality as it contains less methane and more nitrogen (dilutant) compared to type H. This variation in composition of the fuel affects the emissions. A fuel with lower LHV has typically a lower flame type and hence it produces less NOx. The NOx and CO emissions from the two sites are shown in Figure 5 as a function of the load. The measured emissions, converted to 15% O_2 and normal condition, are well below the required limits for both the NOx and CO. It should be noted that TA Luft requires compliance to the emission limits between 70-100% load. The unit operating with a lower LHV natural gas shows as expected slightly lower NOx emissions. The NOx emissions measured are well below the TA Luft requirement and even as low as 10 ppmv for a large portion of the load range.

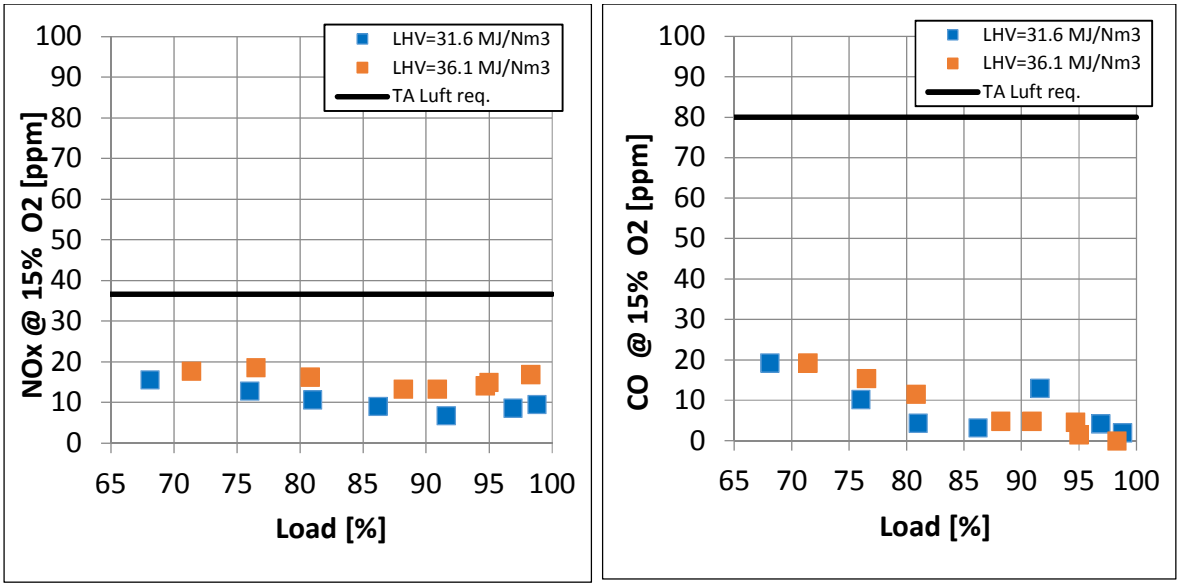

Figure 5. Measured NOx (left) and CO (right) emissions for different quality of natural gas fuels. Values converted to 15% O_2.

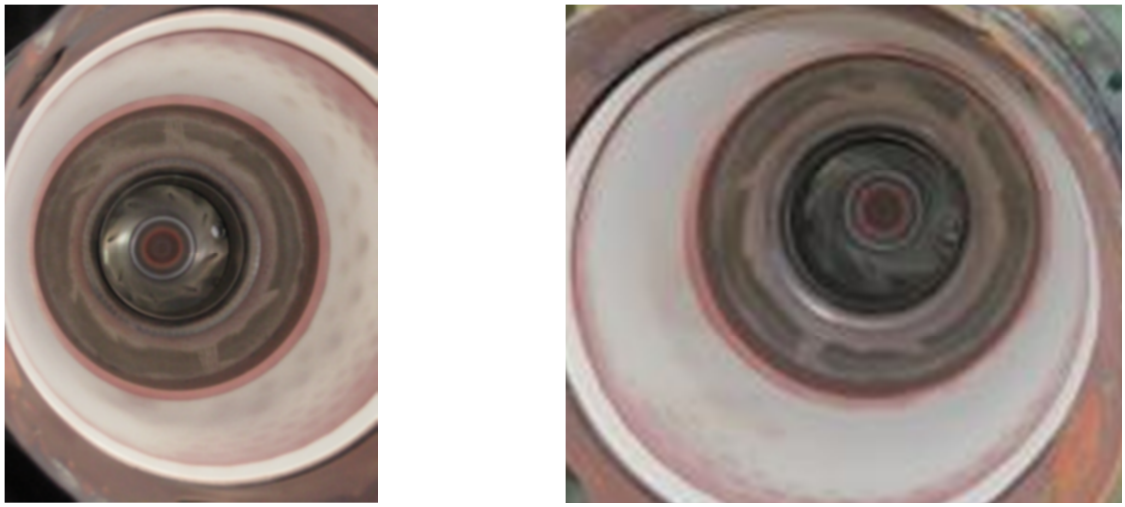

Figure 6. The combustor flame tube after 8000 hours (left) and 16000 hours (right operation.

The combustion chambers are subject to harsh environment and it is therefore required to evaluate them during the annual inspection. Figure 6 shows the interior of one of the flame tubes from the unit operating at the starch manufacturing plant. The left photo is after 8,000 hours and the right photo is after the 16,000 hours. A key factor is to avoid local cold regions in the combustion zone and therefore the OP16-3B has been equipped with thermal barrier coating (TBC) along the liner wall, enabling a higher temperature of the wall. It is important to ensure that the TBC remains in good condition during the operation. From the photos one can see that the TBC is in very good condition after 16,000 hours of operation without any sign of cracks. The darker areas seen are from the location of the impingement jets on the outer surface of the flame tube. All four combustion chambers showed the same good condition after 16,000 hours.

5.2.Rotor module

The heart of the OP16 is the all-radial rotor module with the compressor and turbine mounted in a back-to-back configuration. The turbine impeller is the component seeing the toughest combination of temperature and stress levels. The condition of the hot flow path, as well as the compressor section, is inspected during the annual site visits.

Figure 7 shows the turbine and compressor impellers after 16,000 hours operation at the starch manufacturing plant. It should be remembered that this unit is running 24/7 at max load. As can be seen from these photos both components are in good condition. The turbine impeller (left photo) shows no signs of overheating or rubbing against the shroud. The same was found for the complete turbine impeller section. The compressor was also inspected (right photo) and it was also found to be in good condition. It was very clean and no material loss was found. It can be concluded that the rotor module is in good condition after 16,000 hours of operation.

Figure 7. The turbine impeller tip region (left) and the compressor leading edge section (right) after 16,000 hours operation.

6. Conclusion

The benefits of CHP solutions have been recognized by many end-users in Europe. In particular, smaller industries with a demand for heat or steam in their process have discovered the benefits of simultaneously producing electricity and heat/steam. Most often the requirements for steam/heat are the primary selection criterion when choosing the gas turbine model.

During the recent years OPRA Turbines has seen an increasing number of requests from smaller industries in Europe and worldwide to utilize the OP16 gas turbine in CHP applications. As a result the number of units installed is growing rapidly. The OP16 gas turbine combines high overall fuel efficiency with robustness and low operating costs. With its advanced combustion technology the OP16-3B gas turbine meets the current and future emission regulations.

References

[1] https://setis.ec.europa.eu/system/files/Technology_Information_Sheet_Cogeneration.pdf

[2] Axelsson, L.-U. and Beran, M., "Experience from operating the OP16 gas turbine on alternative fuels," in *PowerGEN Brasil*, São Paulo, 2013.

[3] 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, 2014.

[4] Bouten, T., Beran, M. and Axelsson, L.-U., "OP16-3C: Advanced Gas Turbine Technology for Utilization of Low-Calorific Fuels", in *PowerGEN Europe*, Cologne, Germany, 2014.

[5] Lefebvre, A. H. and Ballal, D. R., "Gas turbine combustion", CRC Press, 3rd ed., 2010.