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Whitepaper
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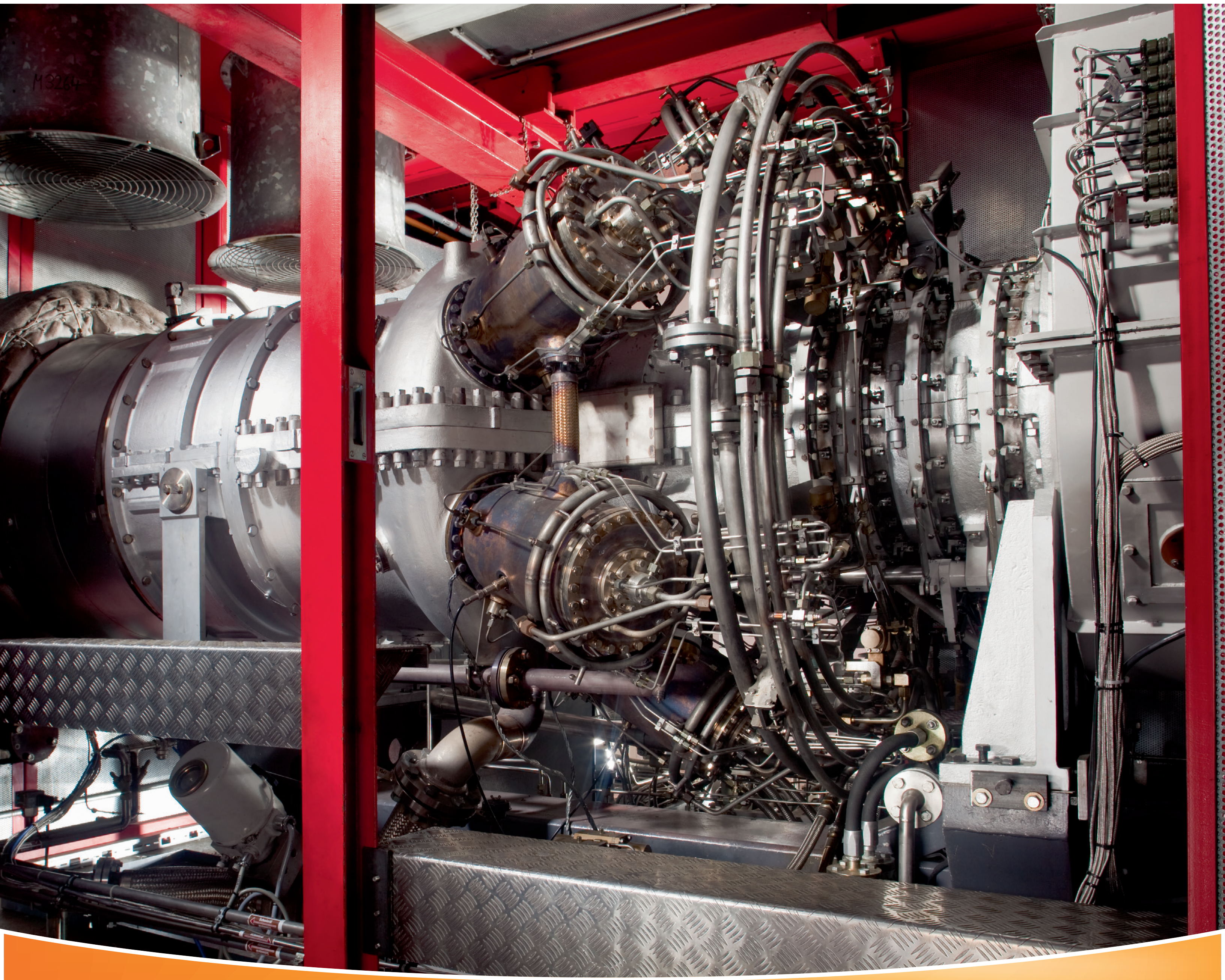
Influencing factors and measurement parameters for gas turbines and their importance for optimizing efficiency and emissions.



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Gas turbines and their areas of application in industry

Gas turbines have their origins in the development of aeronautical jet engines. Thanks to their outstanding performance in the peak load range, they have proven themselves as crucial and reliable components in numerous industrial applications. Gas turbines are frequently used in the power and heat generation sector, as well as in the oil and gas compression markets.

In industrial energy production, gas turbines ensure that peak demands are satisfied for either power or heat production. Frequent areas of use are gas turbine plants (either single or combine cycle), combined heat and power (CHP) plants, and cogeneration plants. A particularly high level of energy efficiency can be achieved using a combination of gas and steam turbines.

In the oil and gas industry, gas turbines are in use as mechanical drives for pumps, gas compression, fluid in the transportation and processing of raw materials. Turbines are used for gas injection or for increasing pressure in natural gas pipelines, mostly in midstream operations. For example, water injection pumps in oil production or for transporting refinery products through pipelines are driven by gas turbines.

Gas turbines are operated with liquid and gaseous fuels such as natural gas, gasoline, diesel, heating oil or petroleum. In the peak load range, energy can be produced in large quantities and with a high overall level of efficiency. Optimizing the fuel and exhaust to the highest level of efficiency involves a complex interaction between the exhaust gas emissions and the combustion process settings. For this reason, during the commissioning, operation and servicing of gas turbines, certain measurement parameters which influence the combustion process are regularly recorded. Based on these data, the parameters which are responsible for an economic, regulation-compliant and resource-saving operation of the turbine can be controlled and optimized.

For combustion tuning and testing, it is important to understand the function of the process and the influence of the individual measurement parameters on the performance and pollutant emission of gas turbines. In addition to basic knowledge, this whitepaper offers the practical know-how needed to optimize the efficiency of gas turbines and to adjust the emissions to comply with permitted emissions levels.

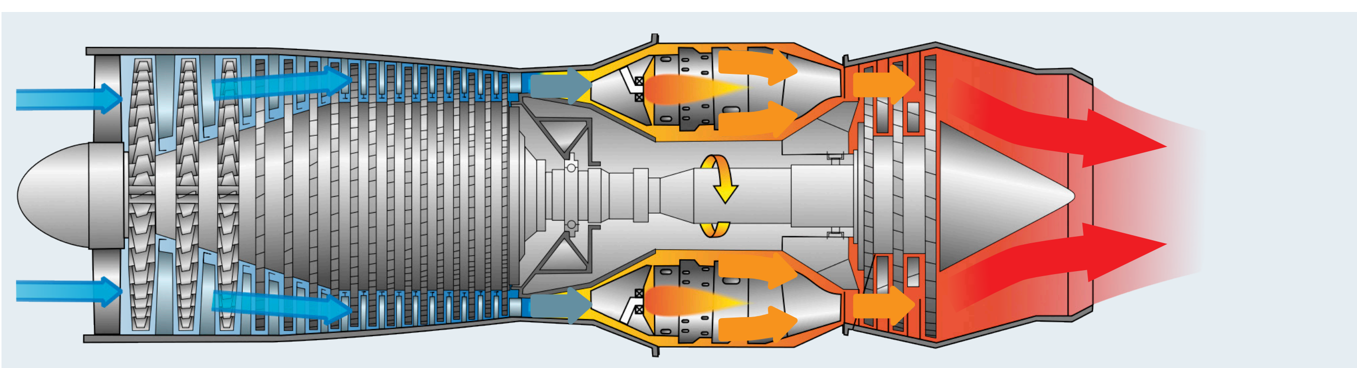


Fig. 1: Gas turbines are combustion engines which consist of three components: a preliminary compressor, the central combustion chamber and the actual turbine.

Function and efficiency of gas turbines

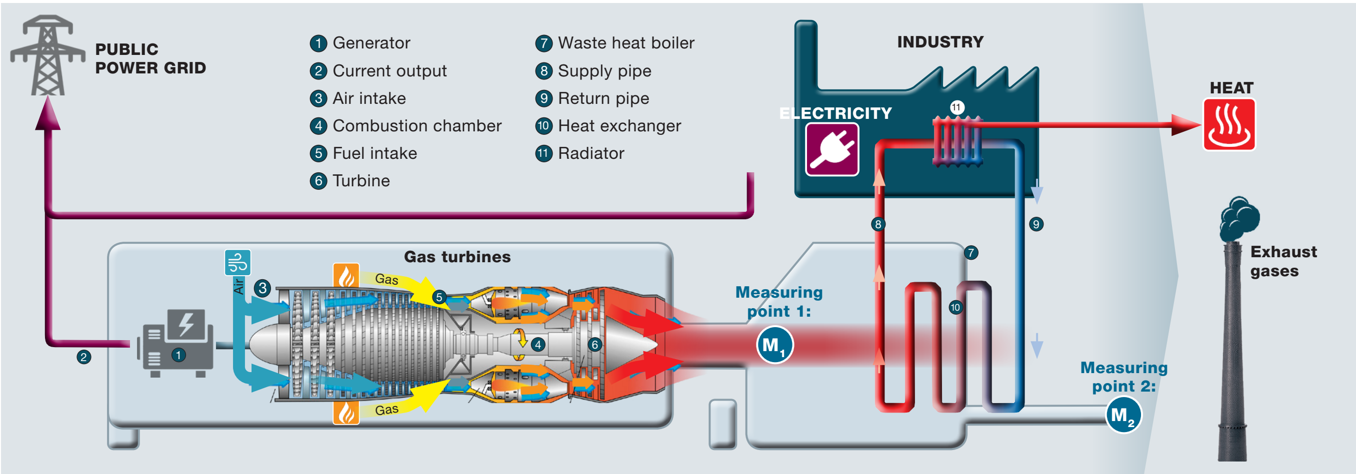


Fig. 2: Schematic combustion process of a gas turbine with heat recovery boiler. Monitoring combustion process at measurement point 1 (M1), monitoring emission limit values at measurement point 2 (M2).

Gas turbines are combustion engines which consist of three components: a preliminary compressor, the central combustion chamber and the actual turbine (Fig. 2:).
The design, performance and size of gas turbines differ depending on the application and area of use. However, their working principle is always the same, and is based on the thermodynamic cycle process according to James Prescott Joule ("Joule process"). Air is compressed via the blading of one or more compressor steps, and then mixes with a gaseous or liquid fuel in the combustion chamber, ignites and combusts. A hot gas is produced from this mixture of compressed air and combustion gas, which can reach temperatures of 1,892 °F (+1,000 °C), and which flows to the downstream turbine component, and expands. Thermal energy is converted into mechanical energy. Subsequently, in the expansion turbine, the energy-rich, hot exhaust gas expands almost to ambient pressure, losing its velocity. During the expansion process, the exhaust gas transfers power to the turbine. Approximately 2/3 of this power is needed to drive the compressor (air intake). A directly coupled generator (Fig. 2 1) converts the mechanical energy into electrical energy. Roughly $^{1}/_{3}$ of the power output remains available on the low pressure side for a second drive, for example for driving a generator, rotor, compressor or pump, before the hot gas is diverted to a downstream heat recovery boiler (fig. 2 11) for the purpose of heating buildings.

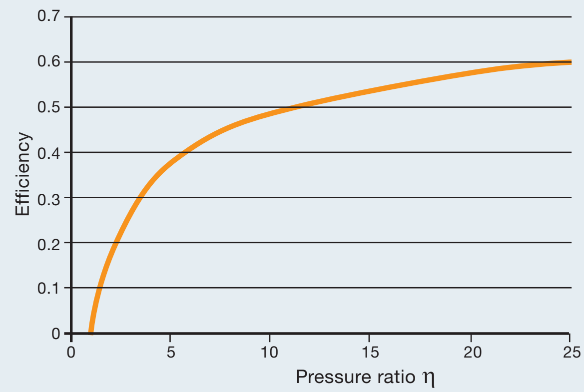
Degree of efficiency of a simple gas turbine process

The efficiency of a gas turbine plant is above all dependent on the temperature in the combustion chamber. The higher the temperature, the higher the degree of efficiency. Innovative materials for turbine blades, ceramic heat shields or turbine blades with sophisticated cooling systems today allow temperatures up to approx. 1,892 °F (+1,500 °C), which in a large turbine can mean over 300 megawatts of output and an efficiency of up to 40 %. In comparison to the degrees of efficiency of steam turbines, which can be over 60 % in the low temperature range, this does not appear high. However, gas turbines strength is in their relatively high exhaust gas temperature and speed with which they reach their top performance. Gas turbines can not only be started within just a few minutes, they also display a high output change speed, frequently over 10 % of the maximum output per minute.

The combination of gas and steam turbines (Combined Cycle Gas Turbine CCGT) achieves an accordingly high level of electrical efficiency, as the hot gas from the combustion process of the gas turbine can be used to heat the steam boiler.

Possibilities for increasing efficiency

The efficiency of gas turbines can be increased by the measurement and regulation of turbine emissions (O_2, CO, NO and NO_2 (Fig. 2 M_1) and the optimal adjustment for different load points. However, the design also has an effect on the efficiency of a turbine. In mechanically more complex, dual-drive gas turbines, the compressor and the turbine work on two different axles, usually rotating at different speeds. By adjusting the number of revolutions, a further increase of efficiency can be achieved. If the compressor and the turbine are on the same axle however, as is the case in many single-drive turbines, a mechanical increase of the efficiency is not possible.



$$\eta' = \frac{P_{T'} - P_{V'}}{\dot{Q}_{zu'}} = 1 - \frac{1}{\Pi^{\frac{\kappa-1}{\kappa}}} = 1 - \frac{T_1}{T_2}$$

Fig. 3: Degree of efficiency of a simple gas turbine process

Emission characteristics of gas turbines

Exhaust gas emissions and their properties

During the combustion process, the main emissions (CO_2, N_2, H_2O and O_2) are present in Vol% concentrations. Apart from this, smaller quantities of pollutants (CO, HC, NO_x, SO_x) in ppm (parts per million) concentrations, as well as volatile organic compounds (VOC), hazardous air pollutants (HAP) and fine particulate material (PM) are formed. Depending on the sulfur content of the fuel used, VOC sulfur emissions occur (primarily SO_2).

The nitrogen oxide formation is dependent on the fuel/air ratio and the combustion temperature. NO_x increases with rising temperature in the combustion chamber as well as exponentially with the increase in burner air input temperature, the combustion chamber entry pressure and the duration in the flame zone. With increasing water or steam injection, NO_x decreases exponentially, as it does when the specific humidity is increased.

Most gas turbines work with a large quantity of excess air. A part of this air can be diverted to the end of the flame, thus reducing the flame temperature. The extension of the flame zone also reduces the flame length, and therefore shortens the duration of time which a gas molecule remains at NO_x-formation temperatures.

After the stoichiometric flame temperature is reached, the thermal NO_x production accelerates. The greatest challenge in regulating gas turbines is the fact that an increase of the fuel/air ratio towards “lean” (more oxygen) reduces the formation of NO, but also increases the CO emissions.

Analyzing exhaust gas concentrations correctly

The concentration of the released exhaust gases provides important information on the efficiency of the combustion and how it can be increased. The O_2 content in the flue gas can be used to analyze the ratio of the fuel/air mix, for example. CO and NO_X values provide information on the current status of the system and the adherence to the emission limit values.

The air input and the correlating combustion chamber temperature influence the emission behavior of the gas turbine: With increasing oxygen input, the temperature in the combustion chamber sinks. An increased air input with its consequent lowering of the combustion chamber temperature therefore leads to a reduction of the NO_X emission, as less thermal NO_X is formed. If the temperature is lowered further, the emission of thermal NO_X is largely eliminated. Very low C_XH_Y values (methane, for example), can under good conditions be achieved with a good fuel/air mixture ratio. Too high an oxygen surplus however, leads to an insufficiently high combustion temperature, so that the flame temperature is no longer sufficient to combust the entire quantity of fuel (HC). The consequence is an incomplete oxidization of CO, which in turn leads to a new increase of CO. However, increased C_XH_Y values and pollutants such as VOCs, HAPs and PM are primarily the result of incomplete combustion. In order to achieve optimum emission behavior, the working range should always be between air deficiency ("rich") and air surplus ("lean"). In order to adhere to legal emission limit values and ensure an economic operation of the plant, the exhaust gas parameters must be regularly measured and the plant regulated accordingly. Meeting both requirements is not always easy, as a conflict can occur between the objectives of adherence to emission permit limits and maximum energy efficiency. The solution is an optimized combustion process.

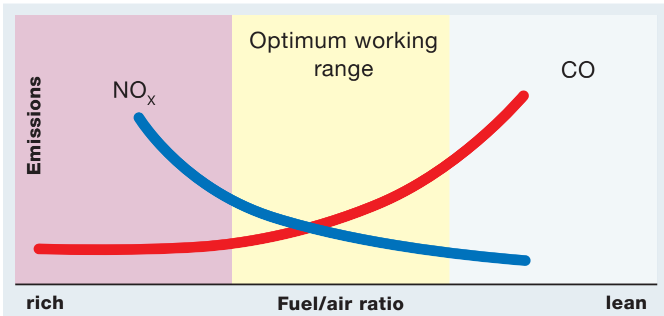


Fig. 4: Optimum working range between "rich" and "lean"

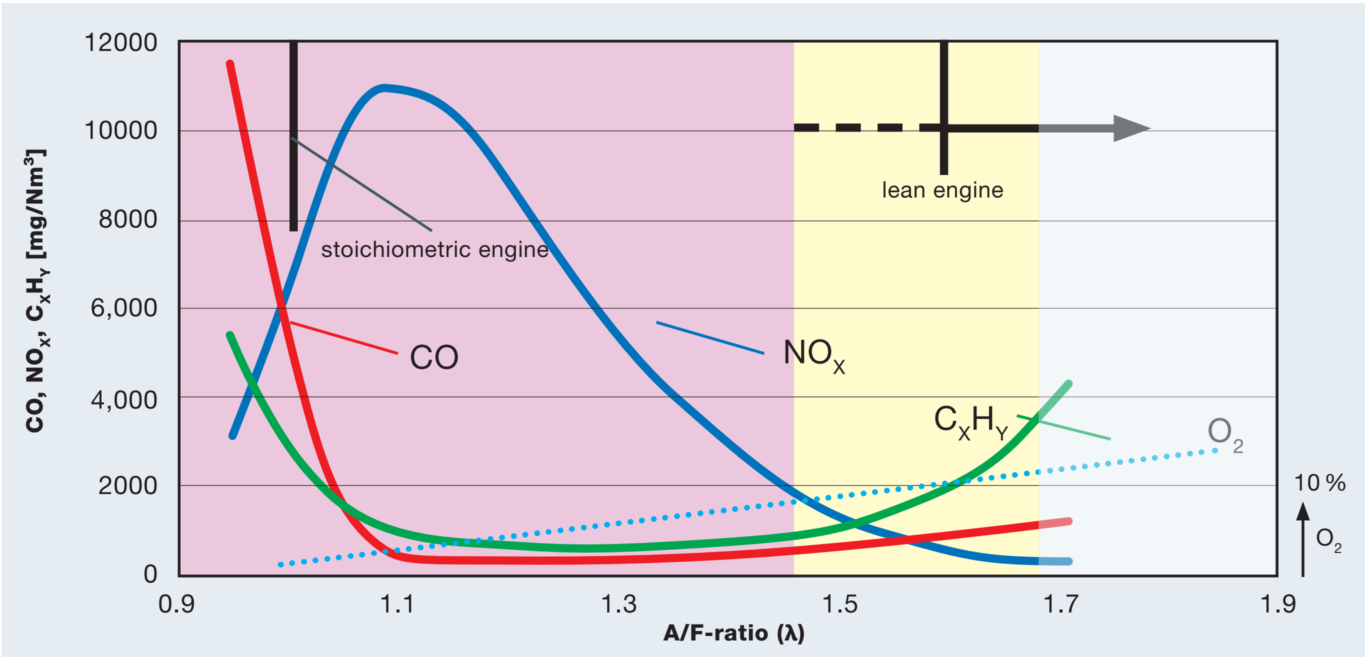


Fig. 5: Emission behavior of gas turbines

Challenges in commissioning, operation and servicing gas turbines

Precise measurement at very low and high gas concentrations

In emission measurements in gas turbines, the challenge is measuring not only at very high, but also at very low gas concentrations. At the right operating point, optimally adjusted gas turbines emit only low levels of CO and NO_x. However, high gas concentrations can occur, for example when the plant is started up for testing purposes, and the emission is measured at differing load levels. In particular during starting up, a gas concentration peak can occur, which will stress or over-range a sensor designed for low concentrations. Using a sample dilution system can allow for high concentration testing and maintain sensor integrity.

In order to achieve as high a measurement accuracy as possible the analyzer system must account for the moisture in the stack. The high exhaust gas humidity, as found in turbines, has a dilution effect on the emissions measurements. Moisture takes up volume and therefore lowers the apparent concentration. EPA testing requirements typically require a “dry” sample to eliminate the variability due to stack moisture. Additionally, one of the NOx species (NO2) will readily absorb into the condensate. This liquid can form in sampling systems and effectively scrub out the NO2 analyte and reduce measurement accuracy. Analyzers that contain a sample conditioning system to remove the moisture and prevent NO2 scrubbing will result in accurate measurements. The testo 350 emissions analyzer can be outfitted with peltier chiller, condensate removal pump, and high velocity sample transport to address the moisture and scrubbing so the NOx measurements are highly accurate.

Reducing nitrogen oxide emissions

Permitted levels below 10 ppm and even at 2-3 ppm are increasingly common. The requirements for NO_x in particular are becoming more stringent. In order to prevent or reduce NO_x formation, combustion control can and must be used.

In the case of liquid fuels, nitrogen oxides can be reduced only by using wet procedures. In this case, the fuel is pre-mixed with water or water vapor. Refitting such plants is not complicated, however it must ensure that the prepared water has a low salt content. Wet procedures have a high water consumption of approximately 110 gpm (25 m^3/h) at 100 MW , and reduce the plant’s efficiency by 5 % – except in the case of steam production with heat recovery.

Dry procedures often referred to as “denitrification”, although it is not the nitrogen which is the object of the scrubbing process, but instead the nitrogen oxides. In exhaust gas denitrification (also known as $DeNO_x$), NO and NO_x are removed from the gas turbine plant’s exhaust gas by primary or secondary measures. In the primary measures, thermal NO formation is largely suppressed by optimized combustion processes. The secondary measures are separation processes. The NO_x contained in the exhaust gas is reduced by absorption, through the injection of a solvent or by reduction to elementary NO (for example through the injection of ammonia).

Pressure loss in the combustion chamber
As the heat release during the combustion process is not uniform, pressure changes occur in the combustion chamber. At certain frequencies, these pressure changes can be amplified into pulsations with destructive effects, causing damage to the plant.

Pressure loss in the combustion chamber is a fundamental challenge, as it has effects on the fuel consumption and the power output. The total pressure loss is usually in the range of 2-8 % of the static pressure. This loss corresponds to that of the reduction of the efficiency of the compressor. The result is a fuel consumption increase and a low power output.

Equally important are the factors concerning the satisfactory operation and lifetime of the combustion chamber. The flame must be self-sustaining, and the combustion stable in the range of fuel/air ratios, in order to prevent ignition loss during transient operation. In order to ensure a long lifetime, moderate metal temperatures are necessary, and steep temperature gradients, which cause cracking, should be avoided. Carbon deposits can deform the intermediate section and alter the flow pattern, causing pressure losses. Smoke, on the other hand, is to be avoided for environmental reasons, as is contamination of the heat exchanger. The minimization of carbon deposits and smoke emissions also helps to ensure satisfactory operation.

Suitable measurement technology for recording low and high gas concentrations

Stationary and portable measurements
In the operation of gas turbines, two different measurement systems are used which complement each other. The stationary measurement, which is permanently installed at the measurement site for long-term, continuous measurements often referred to as CEMS (Continuous Emissions Montoring System). The other is the portable emissions analyzer such as the testo 350 Analyzers, which have proven their worth in servicing or for start-up and commissioning a plant. In some locations the Testo 350 has been permanently installed inside the facility or in an enclosure and used in a semi-continuous operation with analog output. Not for compliance but instead for combustion monitoring or tuning.

Many power stations use CEMS for monitoring the total emissions emitted by the stack. However, this information is not always sufficient for establishing all possible faults. For example, it is not enough for the evaluation of the DeNO_x system. The majority of power stations use NO_x reduction systems (e.g. ammonia injection) in order to ensure that the NO_x levels correspond to the local, state or federal regulations. Their frequent evaluation is of fundamental importance in order to be able to achieve the necessary combustion control for a clean and cost-efficient operation of the plant. Portable NO_x emission analyzers can be used to measure the efficiency of the DeNO_x system exactly. The advantage of a portable analyzer is that over the entire combustion process, several tests must be carried out, including before and after the introduction of the NO_x reduction substance. A portable emissions analyzer allows the measurement parameters to be adjusted on site, quickly and without complications.

Sensors for low and high gas concentrations

Due to the low NO concentrations, emission measurements in inspection and adjustment work on low-NO_X gas turbines require a very high measuring accuracy. Ideal for the adjustment of gas turbines is an analyzer such as the testo 350, which combines an NO_2 sensor and a special Low range NO sensor that has the necessary high measuring accuracy, especially in the sub 20-19 ppm ranges. In addition to this, the integrated gas preparation / cooling system with moisture removal and the special Teflon lined sample hoses with high velocity sample transport, provide fast response and protection from NO_2 absorption. Freely selectable dilution levels allow the measurement of high concentrations of up to 20,000 ppm with the CO_{low} sensor (non-diluted measuring range 0-500 ppm). When the testo 350's dilution system is active, the measuring gas for the sensor in slot 6 is diluted with ambient air (or optionally with nitrogen gas) in a controlled manner. For this purpose, the diluting gas is drawn through a separate gas inlet by a pump and a valve operating on the principle of pulse width modulation. A filter is installed to protect the gas path against dust.

With the NO_X resolution of 0.1 ppm, it is easier to identify small changes in the combustion adjustment. This allows critical monitoring or warranty decisions to be made with the highest level of accuracy.

Calculation example: x40

Exposed sensor and instrument display in comparison	Measuring range CO_{low} sensor	Measuring range CO_{low} sensor with dilution factor 40*	Sensor protection: Measuring range CO_{low} sensor with dilution 40**
Instrument display	500 ppm	10,000 ppm	20,000 ppm
CO_{low} sensor	500 ppm	250 ppm	500 ppm → sensor protection through fresh air flushing if 20,000 ppm exceeded

*Additional measurement uncertainty when using single slot dilution 2 % of m.v.

**Measuring range CO_{low} sensor: 20,000 ppm

O_2 sensors at 15 % O_2 reference

A highly accurate O_2 measurement is important in order to determine the proportional parameter "NO_X corrected" without deviation. "NO_X corrected" recalculates the NO_X measured at any given O_2 concentration to a new reference value. In the case of strongly diluted turbine exhaust gases and an O_2 concentration in the turbine approaching 21 %, the measurement accuracy of the O_2 measurement dominates in the "NO_X corrected" calculation.

Innovative exhaust gas analyzers such as the testo 350 have a high level of O_2 accuracy due to their special design. In the testo 350, the fresh air intake is upstream of the gas cooler, in order to assimilate humidity conditions. For "NO_X corrected" under "normal" turbine conditions up to O_2 ~18.5 %, the specified measurement accuracies including O_2 are sufficient. When the measurement uncertainties are considered, the uncertainty contributions of the NO_{low} and NO_2 dominate for "normal" O_2 concentrations. Only after a large dilution of the exhaust gas, i.e. at an O_2 value of 18.5 %, does the uncertainty of the O_2 measurement begin to dominate. If the O_2 measurement is less accurate (e.g. due to failure to compensate for humidity influence ±0.3 %), the uncertainty of the O_2 measurement begins to dominate at about 17.3 %. Due to the normal humidity in the exhaust stack and its diluting properties, an accurate O_2 measurement with 0.01 resolution is important for low NO_X measurements. The testo 350 satisfies this measurement resolution.

If obviously unrealistic measured values are displayed, the sensors should be checked and, if required, calibrated with EPA protocol gas standards. The calibration/adjustment can easily be done in the field by the user or by Testo's service department.

Formula for NO_X corrected (PPM)

$$NO_X \text{ corr.} = (NO + NO_2) \cdot \frac{21 - O_2 \text{ ref}}{21 - O_2 \text{ mess}}$$

with	NO, NO_2	measured concentrations (ppm)
	O_2 ref	O_2 reference value (%)
	O_2 mess	measured O_2 concentration (%)

Optimum adjustment of combustion processes in gas turbines

Exhaust gas analysis with testo 350

The requirements placed on an analyzer for the analysis of emission and combustion can vary depending on the combustion application. For the correct adjustment and maintenance of gas turbines, a precise O_2 value with a low NO_x content and CO sensitivity is necessary. The testo 350 measures the low measuring range (0.1 ppm) just as accurately as the high ranges which need to be determined for the purposes of turbine testing. Proven technology, an optimized O_2 measurement and the easy-to-use interface ensure maximum precision in any measurement procedure.

The wireless Bluetooth operation in a radius < 328 ft (100 m) allows the combustion parameters to be displayed in a safe place and not at the sampling point. The large on-board memory and the fresh air flushing via the automatic test program allow flexible long term (from hours to about one month) data logging. The brilliant color graphic display and the intuitive software easyEmission ensure a high level of user convenience. The testo 350 is the perfect solution for the gas turbine tuning, optimization and testing.

The exhaust gas analysis system testo 350 for highly precise emission measurements

testo 350 – Advantages at a glance

Highly precise NO_x measurement with combined NO_2 and NO_{low} sensor:
- Highest measurement accuracy with a resolution of 0.1 ppm during testing and adjustment work on low NO_x gas turbines.
- Protection from NO_2 absorption through integrated gas preparation peltier chiller and special exhaust gas probe.

CO_{low} sensor with dilution system:
- Freely selectable dilution levels allow accurate measurements up to 20,000 ppm.
- Measuring range (dilutions system) up to factor 40 (2x, 5x, 10x, 20x, 40x).
- Overload protection without interruption of measurement ensure secure work processes.

Sensor Calibration by the user:
- Easy and precise calibrations on site.

Convenient measurement at different load levels, and long-term measurements:
- A fresh air valve can be fitted for the measurement of different load levels or for long-term measurements. The exhaust gas probe simply remains in the exhaust stack.

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Summary

Gas turbines are crucial and reliable assets for energy production. The challenge for the service engineer is to collect precise measurement of not only very low NO_x and CO measurements, and also high exhaust gas emissions. With these parameters, the engineer can regulate the plant optimally while adhering to the environmental permit conditions.

The exhaust gas analyzer testo 350 measures and records all relevant exhaust gas parameters on gas turbines quickly and highly accurately. Using these data, the engineer can reliably check and control the efficiency of the plant.

Subject to change, including technical modifications.

More information at www.testo.com

More information on the exhaust gas analyzer testo 350 as well as answers to your questions on emission measurement on gas turbines from our experts at www.testo.com

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