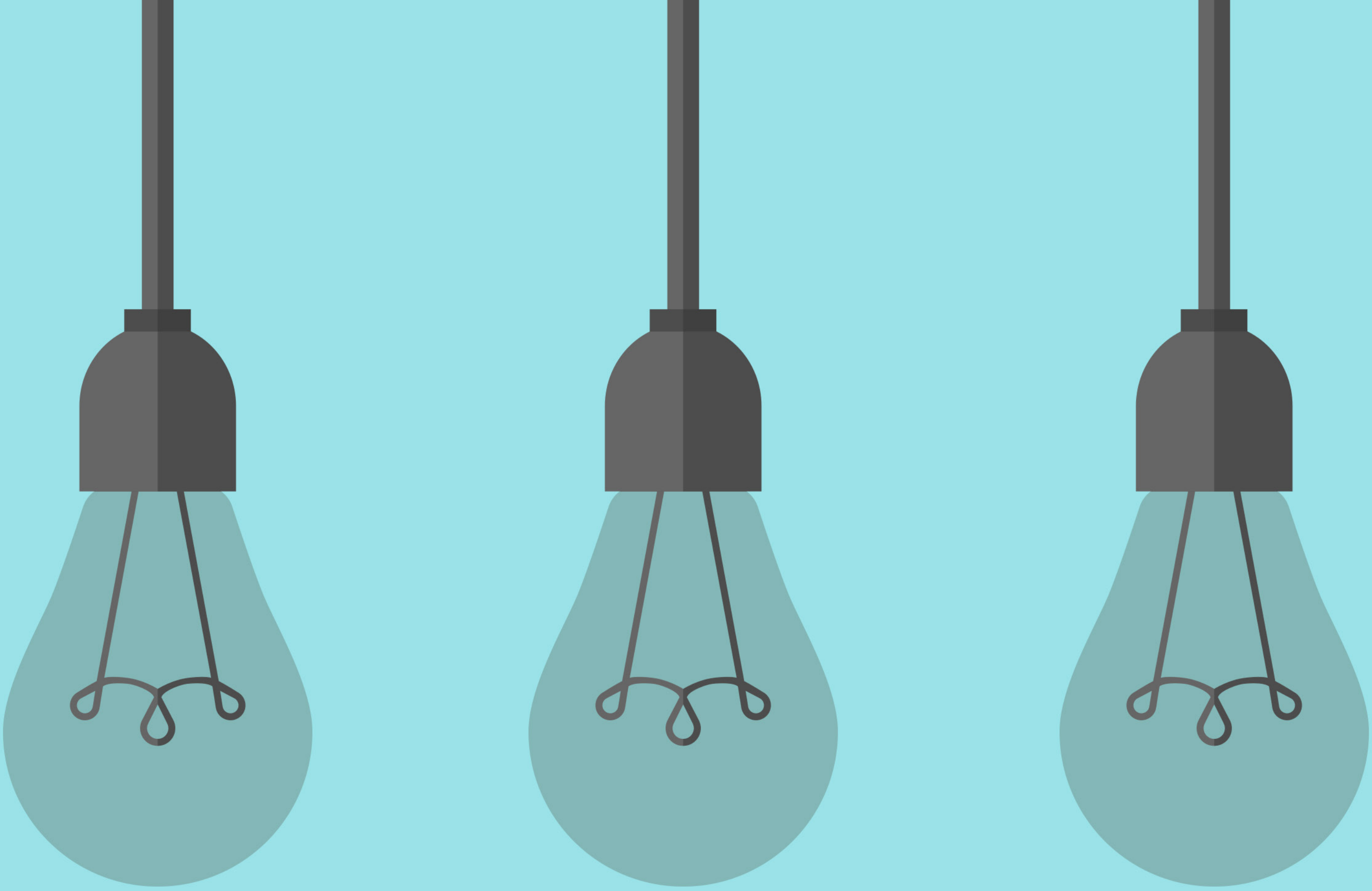


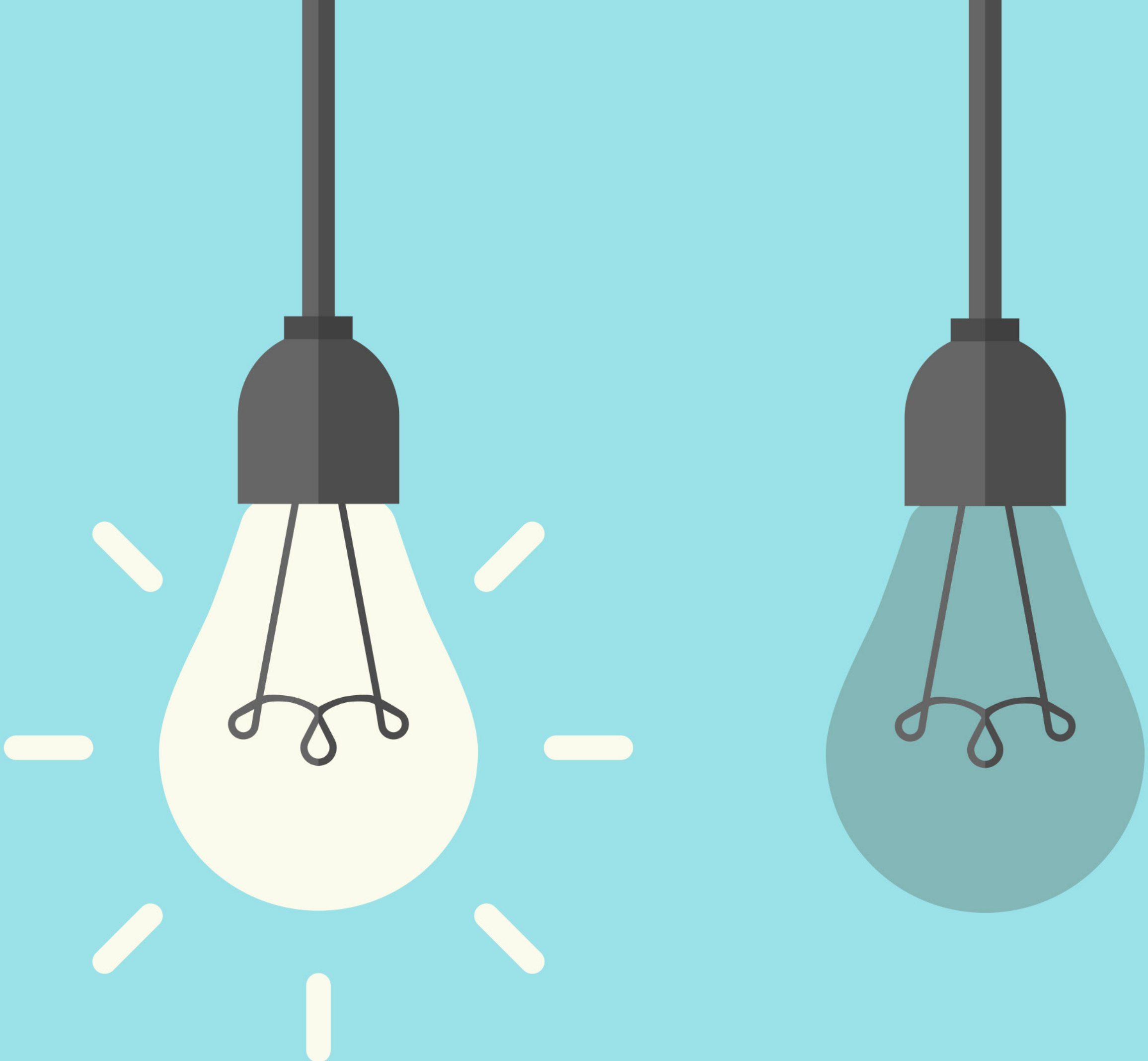
SMART COMBUSTION ANALYSIS

Dr Peter Geiser, Dr Viacheslav Avetisov, Dr Junyang Wang and Larry E. Sieker, NEO Monitors, Norway, overview the evolution of TDLAS technology.

Combustion is an important part of the refining industry's 'Smorgasbord of Measurements'.[1,2] Boilers, heaters, and furnaces all generate heat and power by combusting hydrocarbons. As a consequence of the chemical reactions of a combustion and the objectives to maximise efficiency and reduce nitrogen oxide (NO_X) emissions, oxygen (O_2) concentration measurements are used to control excess air to the combustion zone. An additional measurement of carbon monoxide (CO) can provide a feedback on the O_2-set point as well as being used to monitor CO breakthroughs to avoid fuel rich operations.

Several different technologies were developed over time to perform combustion optimisation, and tunable diode laser absorption spectroscopy (TDLAS) has proven to be an excellent choice due to its inherent advantages.[1] TDLAS is based on evaluating a recorded absorption spectrum; the latter includes one or more absorption lines of the gas that is to be measured. Recent advances in TDLAS, and especially the way a spectrum is analysed, has opened new opportunities and added functionality to combustion analysers.

This article will discuss a new signal processing approach that helps extract more information than



before from the acquired spectrum. The approach has been designed to help create a new path forward for smart combustion analysers and enables an evolution of simple combustion analysis towards a combined process optimisation and safety instrument.

Combustion control

Gas analysers based on TDLAS have been used for many industrial process control and emission monitoring applications and are well-accepted throughout multiple industries. The advantages of performing measurements directly in the process (in situ) include fast response, high selectivity and high sensitivity, which makes efficient process control possible. Furthermore, in situ measurements require little maintenance and thus lower operational expenditures.

A challenge using TDLAS for combustion analysis, however, is the required CO measurement range. An upper boundary of a few thousand ppm is necessary, as shown in Table 1, where an overview of generic conditions and a typical gas matrix is provided. CO has several absorption bands in the infrared region. While the band around 1.5 μm is too weak to achieve the desired sensitivity, the band around 4.6 μm is too strong and thus limits the upper boundary of the measurement range. This leaves the 2.3 μm band where not only methane (CH_4) has strong absorption bands but also some water vapour (H_2O) absorption lines are very strong at high temperatures. The identification of a CO absorption line that is free of interference throughout a wide range of process conditions is very challenging or even impossible.

In order to combat this challenge, NEO Monitors has developed a single combustion analyser, which is designed to provide combined measurements of O_2, CO, CH_4, H_2O and process temperature. The LaserGas^{TM} iQ^2 combines a new signal processing technique with two lasers in a single compact unit; one laser is used for measurements of O_2 and optionally temperature, the other one for the remaining components.

A new approach

The availability of more computing power permits analysers to perform more complex mathematical calculations like real-time multivariate analysis (MVA). MVA is commonly used in near-infrared spectroscopy as an effective method to deal with unresolved spectra and overlapping absorption bands. MVA performs mathematical transformations of the measured data (in this case absorption spectra) and the calibration datasets (reference spectra). Since the concentration output from MVA depends solely on the calibration data, the absorption spectroscopy theory is not directly involved, and thus the reliability of the results may be questionable. Consequently, a new approach was developed in order to overcome this problem.

The in situ real-time overlapping spectral separation (IROSS) combines MVA and spectroscopy models based on traditional TDLAS for reliable concentration measurements.[3] The technique incorporates control of MVA data processing to ensure robustness of the spectral separation for in situ applications where conditions are often harsh due to high temperatures, dust loads, flames, and rapid changes of gas compositions. For example, in the combustion process, where the conditions at start-up are completely different than those occurring during normal operation.

Compared to using a pure mathematics-based MVA model, IROSS is less prone to providing an unreliable result as it is supported by an implemented validation check. Thus, the benefits of traditional TDLAS, in situ and real-time measurements, are maintained.

An important advantage of the MVA-implementation is the fact that not only a single line is investigated, like in traditional TDLAS signal-processing techniques, but the whole spectrum is considered. This enables adaptation to changing conditions. The analysers' capabilities can also be extended by increasing the amount of information that can be extracted from the spectrum, i.e. IROSS is not limited to the mere separation of overlapping spectra.

Table 1. Typical gas matrix and conditions for combustion applications

Species	Concentration range
Water vapour (H_2O)	10 – 30 vol%
Carbon dioxide (CO_2)	5 – 15 vol%
Carbon monoxide (CO)	0 – 1500 ppm
Oxygen (O_2)	0 – 10 vol%
Methane (CH_4)	0 vol% - LEL
Nitrogen (N_2), residual hydrocarbons (CxHy), nitrogen oxides (NO_X)	Rest
Temperature range	500 – 1400˚C
Pressure range	Slightly below or around ambient

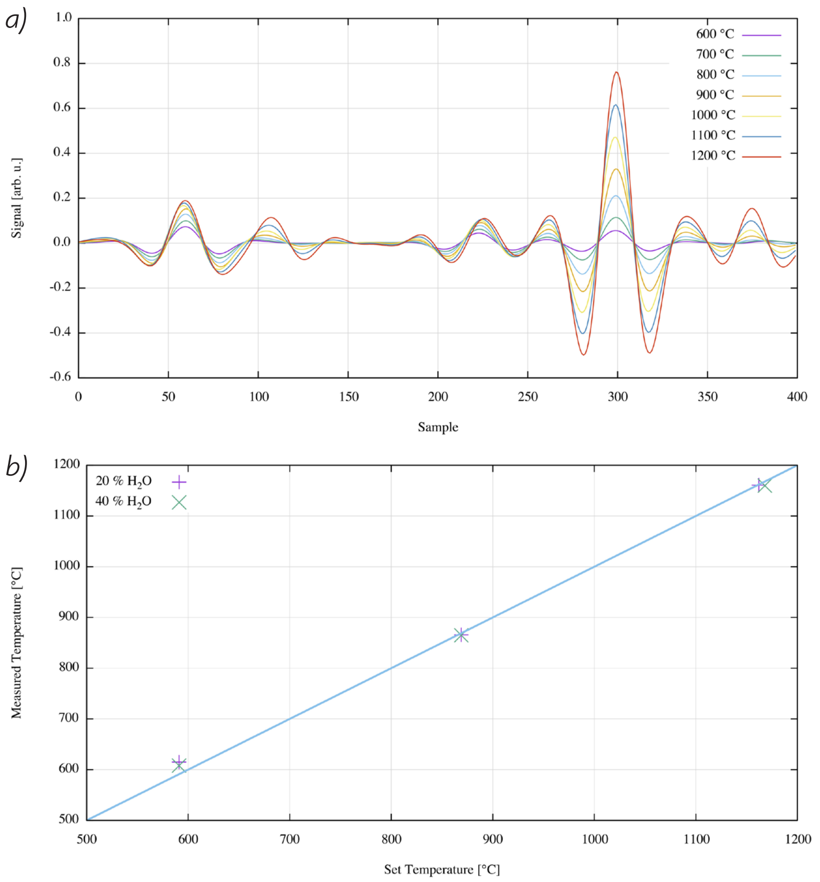


Figure 1. a) Absorption spectrum of water vapour for process temperatures between 600˚C and 1200˚C. b) Results of spectral temperature measurement using IROSS for two different H_2O concentrations.

Combustion safety

Since the detection of low O_2, high CO, or CH_4 in a combustion process can also indicate unsafe operation, the combustion analyser is now evolving from just a process analyser providing 'air to fuel ratio' feedback to the basic process control system (BPCS), to the utilisation of the analyser for the burner management system (BMS) implementation of safety instrumented systems (SIS) per IEC 61511 and API 556 recommended practices.[4]

Some of the reasons TDLAS is suitable for the BMS include:

- The ability to measure across the combustion zone instead of an 'extraction point measurement' – an integral measurement along the line-of-sight represents the conditions in the combustion zone much better than a measurement at a single point, typically close to the wall.
- The ability to accurately measure CO and CH_4 concentrations without the presence of O_2 in the fuel rich combustion zone – unlike other technologies, such as thermal conductivity detectors, TDLAS does not need other gases to be present to perform a measurement of the target species.
- The inherently fast response time – TDLAS is able to provide response times of seconds, which is essential for the detection of rapid concentration changes within highly dynamic combustion processes.

Nevertheless, the desire to also use in situ TDLAS for safety applications introduces new challenges for the technology, since exceptional conditions must be considered.

Toward smart combustion analysis

A key enabling factor for this evolution is the aforementioned IROSS technique. While developed with the focus on enabling true multi-component measurements, the MVA-based technique can measure other components as well.

The average temperature over the whole furnace is an important additional process parameter that can be used to ensure proper and safe operation. For example, a simultaneous drop in temperature and increase of CH_4 may indicate that the combustion is incomplete due to a possible malfunction of the burner. In addition, due to the ideal gas law and the temperature-dependency of absorption spectra, the measured concentrations must be corrected using the process temperature.

Immersion temperature probes like thermocouples can be used to feed real-time measurements into TDLAS instruments. These sensors, however, suffer from rapid degradation at higher temperatures and must be replaced frequently. Furthermore, temperature probes are measuring only at a single point in the process, typically close to the wall, and the results are not necessarily representative for the whole process and can thus not always detect potential burner malfunctions.

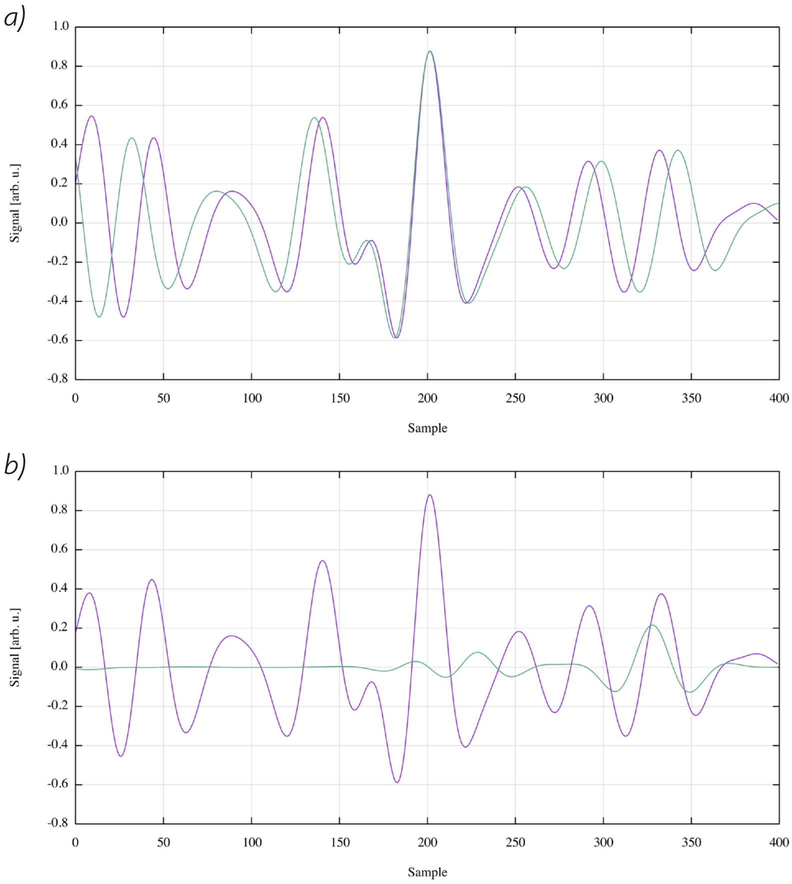


Figure 2. a) Linearity change of laser tuning. b) Presence of an unexpected absorption line.

Using a point sensor can also lead to wrong temperature compensation which results in incorrect concentration readings. A better approach would be the determination of the temperature using recorded absorption spectra. In this way, temperature and gas concentration are measured in the exact same volume across the furnace and much better process information would be available.

TDLAS is also capable of measuring the gas temperature. The strength of an absorption line, the probability that the laser light is absorbed on its way from the transmitter to the receiver, is only a function of temperature and not pressure. So, if probing two lines of the same species with a different temperature-dependency, the ratio will provide information about the actual temperature in the process; in this case, the average temperature in the same volume where the gas concentration measurement is performed.

Best known is the usage of two O_2 absorption lines. However, in cases where little or no O_2 is present in the process, a spectroscopic temperature measurement is not possible. An alternative is to use H_2O absorption lines instead. While H_2O is an omnipresent interfering gas and thus a frequent obstacle for TDLAS concentration measurements, it can also be used to determine the process temperature. However, the simple line-ratio approach may not always be suitable for H_2O because the H_2O self-broadening for different absorption lines is not equal and thus the ratio of the absorption line amplitudes depends also on the H_2O concentration. The IROSS technique, on the other hand, not only looks at the amplitudes of two absorption lines but considers the whole recorded spectrum, which can include several lines with different line-broadening and temperature-dependencies. Figure 1a shows the recorded H_2O absorption spectra (second derivative detection) at different temperatures. As can be seen, there are many H_2O lines with different temperature dependences. Consequently, since IROSS has a larger base for analysis, information on both the H_2O concentration and the temperature can be extracted. Figure 1b shows that the temperature determined from the 20 vol% H_2O absorption spectra coincides with the temperature determined from the 40 vol% H_2O spectra.

Smart combustion analysers can adapt to process conditions. Depending on the operation point, the temperature is either measured using O_2 lines or, if the O_2 concentration is too low, a dynamic switch to H_2O-based measurements is performed. Temperature measurements over a wide range of process conditions can be achieved in this way, even under safety-relevant exceptional circumstances. Furthermore, O_2 and H_2O-based measurements can be combined either to increase accuracy by calculating an average value or to verify the consistency of the obtained results. In case of a deviation between the two temperatures, the smart analyser flags it.

The analyser integrity is important for all applications, but even so for safety applications. It must be verified that the analyser is performing as expected and that the measured concentration is correct. A change in laser characteristic, for example, would mean that the concentration readings are no longer reliable. Analysers have built-in functions to perform such a 'health check'. However, IROSS is enabling even more smart functionality. Again, by investigating the whole absorption spectrum and not just the single absorption lines, the amount of information that can be extracted is increased. The MVA-based technique uses the calibration datasets as input for its analysis. If the laser wavelength has drifted or if the linearity of the wavelength scan has changed (Figure 2a), a comparison with the reference spectrum will reveal that and the smart analyser will flag it.

If one or more additional absorption lines are found, this can also be identified (Figure 2b). While it might not be crucial for the concentration measurement itself if the additional absorption line is not interfering with the targeted line, it could mean that something else happened in the process that is compromising the safety.

Conclusion

To summarise, TDLAS technology is currently evolving from the classic 'single laser – single gas' analyser to a 'single laser – multi gas' or even 'multi laser – multi gas' instrument addressing complete applications. Operators always want to be able to rely on the integrity of their instruments and the provided measurement results. This need is addressed by conducting continuous health checks, detecting unexpected behaviours and malfunctions; there is even the potential for self-repairing. While the first steps toward smart combustion analysis have been taken, there is sure to be more on their way in the future.

References

1. GEISER, P., and AVESTISOV, V., 'A Smorgasbord of Measurements', *Hydrocarbon Engineering*, Vol. 23, No. 5, (May 2018), pp. 81 – 84.
2. GEISER, P., and AVESTISOV, V., 'Switching to in situ analysis', *Hydrocarbon Engineering*, Vol. 23, No. 10, (October 2018), pp. 67 – 70.
3. WANG, J., AVESTISOV, V., and GEISER, P., 'IROSS - Advanced signal processing for near- and mid-infrared in situ applications', Field Laser Applications in Industry and Research (FLAIR), Assis, Italy (2018).
4. 'Instrumentation, Control, and Protective Systems for Gas Fired Heaters', API Recommended Practice 556, Second Edition, (April 2011).