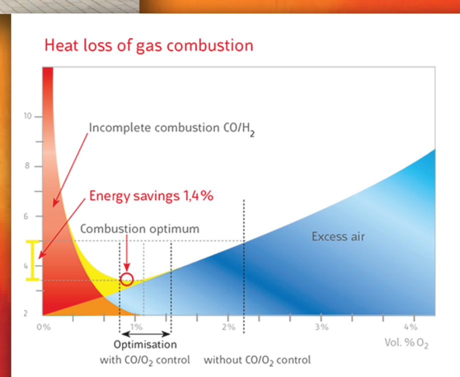
Savings by using O_2, respectively CO control			
Function	Partial Load	Middle Load	High Load
O_2 control	1.19 %	1.47 %	1.20 %
CO control	1.96 %	1.85 %	159 %
Operating hours	1600	5600	800
Fuel costs/h 0.35/Nm³			

Savings/year at 0.35 €/Nm³	
O_2 control	11 537 €
CO control	additionally 3 291 €
Total	14 828 €



Burner & Combustion

Sensory Combustion Optimisation of Gas Combustion Systems

Sensors and Systems for Combustion Engineering

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Sensory combustion optimisation of gas combustion systems

by **Frank Hammer**

Today, the quality of gas is already subjected to non-negligible fluctuations in the natural gas grid. New repositories, an altered distribution structure, and, especially, the supply of regenerative gases such as biogas and wind-hydrogen increasingly alter the concentrations of hydrocarbon, hydrogen, and inert gas components in the gas and thus its combustion properties. This has an effect on the combustion process and therefore on the efficiency and emissions of gas furnaces. A combustion control system to compensate for these gas quality variations and other disturbances on the process is therefore essential. In particular, the use of robust exhaust gas sensors for the measurement of oxygen (O_2) and for the detection of unburned gas components such as CO, H_2, and HC (CO_e) allow simple control strategies for the self-adaptive optimisation of combustion and increases the reliability and operational safety of the gas combustion system.

The objective of any combustion control system should be the maximisation of efficiency at the simultaneous minimisation of pollutants. The influence of the air value λ or rather, the remaining oxygen content on the efficiency and the polluting emissions of a combustion plant is fundamentally shown in **Fig. 1**. Too much excess air leads to exhaust gas heat loss, whilst a lack of air leads to efficiency losses due to incomplete combustion. Ideally, the plant is operated at the optimum air value, which may lie at λ_{opt} = 1.02 in the case of today's plants, shortly in front of the so-called emission edge.

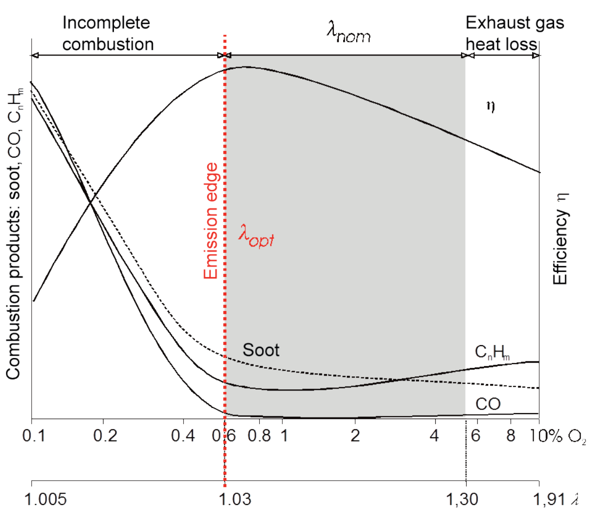


Fig. 1: Typical curve of the pollutant emissions and efficiency depending on excess air

Challenges for every combustion process are presented by gradually changing conditions and quick, externally active disturbance variables, such as:

- Combustion air (temperature, pressure, humidity),
- Fuel (calorific value, temperature, viscosity),
- Contamination (burner, combustion chamber, boiler, exhaust gas duct),
- Chimney (wind, temperature, draught),
- Mechanics (play, hysteresis, component failure).

Typical fluctuations in air temperature of ± 20 °C lead to O_2 changes of ± 1.5 % by volume O_2. **Table 1** shows the influence of additional disturbance variables on the O_2 content in furnace exhaust gas. If a combustion process is adjusted to a certain point, it is "blindly" exposed to these O_2 fluctuations without sensor monitoring. An increase in O_2 according to Fig. 1, leads to an efficiency loss due to an increase in the amount of exhaust gas because of excess air. A reduction in O_2, especially in case of a lack

Table 1: Typical disturbance variables and their effect on the O_2 content in furnace exhaust gas

Disturbance variable for combustion	Typical fluctuation of the disturbance variable	O_2 change in Vol.%
Ambient temperature	± 20 °C	± 1.5 Vol.%
Ambient pressure	± 25 mbar	± 0.8 Vol.%
Calorific value	± 10 %	± 2.0 Vol.%

of oxygen, leads to a risk of incomplete combustion with high polluting emissions of CO_e when exceeding the emission edge. The efficiency drops drastically since unburned combustible gas gets unused outside through the flue.

A monitoring and safe adjustment of the combustion for the compensation of such disturbance variables is thus unavoidable for both environmental and safety reasons. In the follow, the exhaust gas sensor required for this purpose, the classic O_2 control and the even more efficient CO_e/O_2 optimisation that can be implemented as a result are introduced.

THE SENSORS

For monitoring the dynamic combustion process and for the compensation of disturbances, quickly reacting sensors must be placed ideally directly into the exhaust gas duct of the combustion plant. These in-situ exhaust gas sensors are exposed to high loads in flue gas. In addition to the known combustion products, these loads include temperature, pressure, humidity, water steam, additives, HF, SO_2, SO_3, H_2SO, ash, dust, heavy metals, boiler abrasion, vibrations, and so on. Robust, highly dynamic gas sensors based on solid electrolyte ceramics are thus used for this task. The best known example of a solid electrolyte sensor is the λ-probe, which is mainly used in automobile applications.

Lamtec develops and produces its own solid electrolyte sensors for measuring O_2 and detecting CO_e. **Fig. 2** shows an example of the combination probe KS1D for the simultaneous measurement of O_2 and CO_e with relevant data and facts (from left to right: top: thimble-like sensor element/sensor/installation situation of the probe; middle: KS1D probe with measuring gas extraction and built-in fitting/installation situation of the probe; bottom: technical data of KS1D)

Fig. 3 contains a principle drawing of the thimble-like structure of the KS1D probe. It is located in the exhaust gas duct of the combustion plant. The functional ceramics (yttria-stabilised zirconia) separates the reference gas chamber (ambient) from the measuring gas chamber (flue) in a gastight manner. The "inside" of the functional ceramics contains a reference electrode made of platinum, whilst both measuring electrodes for O_2 and CO_e are located on the "outside" of the ceramics in the measuring gas. The O_2 electrode 1 made of platinum and the CO_e electrode 2 made of a platinum/noble metal alloy differ only in regard to material. The different catalytic and electrochemical properties of the electrodes are what permit the detection of CO_e. By means of an integrated heater, the probe is heated to and regulated at temperatures of T = 650 °C. At this temperature, the solid electrolyte ceramics is a good oxygen ion conductor which allows forming both sensor signal voltages U_{S1} between electrode 1 and the reference electrode and U_{S2} between electrode 2 and the reference electrode that can be measured.

The sensor voltage at both electrodes U_{Si} with i = 1,2 initially correspond with the known Nernstian voltage,

$$U_{Si} = U_{0,i} + \mathfrak{R}\, T_i/4F \cdot \ln\left(p_{O2,ref} / p_{O2,meas}\right) \tag{1}$$

which depends on the partial oxygen pressure $p_{O2,meas}$ in the exhaust gas. The oxygen partial pressure of the environment is known as a reference and lies at a constant of $p_{O2,ref}$ = 21 Vol.%. The universal gas constant $\mathfrak{R}$ and the Faraday constant F are also known. A simple 1-point calibration in air where $p_{O2,meas} = p_{O2,ref}$ = 21 Vol.% results in $U_{Si} = U_{0,i}$ and thus directly the sensor-specific offset voltage $U_{0,i}$ at the set sensor temperature T_i.

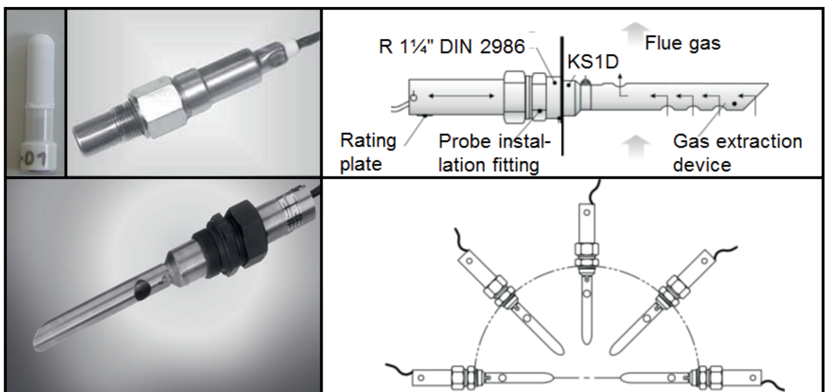
In the presence of combustible CO_e gases, a non-Nernstian sensor voltage U_{COe} forms at the second measuring electrode, which is added to the pure Nernstian oxygen signal voltage. The resulting sensor signal at electrode 2, thus results in

$$U_{S2} = U_{S1} + U_{COe} \tag{2}$$

For the combustible CO_e components, the following results:

$$U_{COe} = U_{S2} - U_{S1} \tag{3}$$

In **Fig. 4**, both signals U_{S1} and U_{S2} of KS1D are shown with respect to the O_2 content in the exhaust gas of a typical combustion plant. In addition, the concentration of the unburned CO_e components is shown in ppm on the second y axis.



	O_2	CO_e
Measurement range	0-21 Vol.%	0-1.000 ppm
Resolution	0,1 Vol.%	1ppm
Precision	±5 % of measured value not better than ±0,3 Vol.%	±25 % of measured value not better than ±10 ppm
Response time t_{60}	<10 s	<2 s

Fig. 2: Combination probe KS1D for the simultaneous measurement of O_2 and CO_e

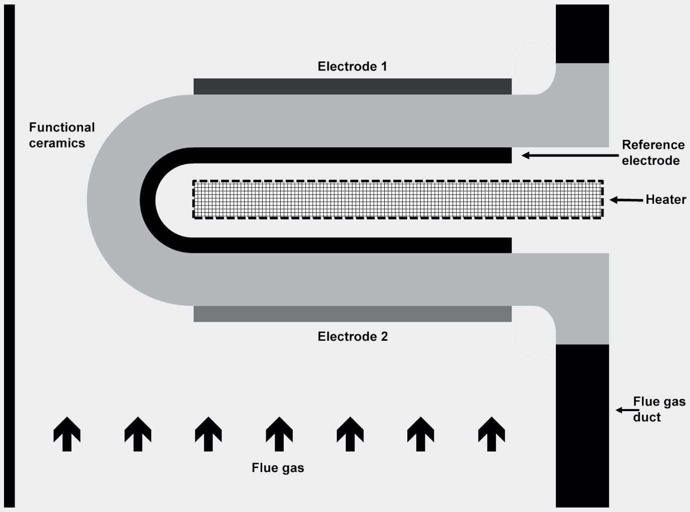


Fig. 3: Functional principle of KS1D

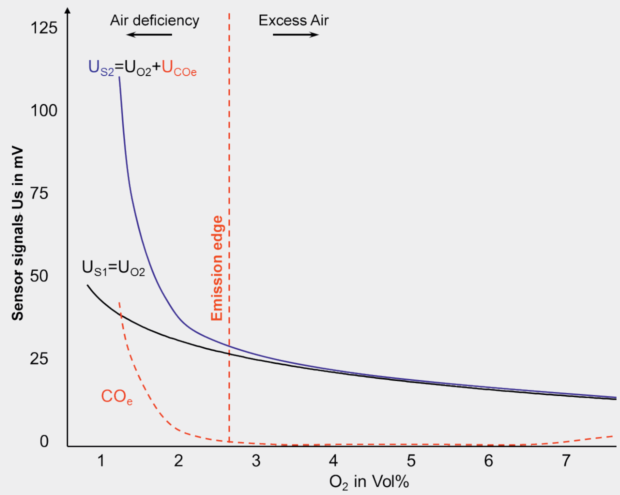


Fig. 4: Principle signal curve of both KS1D sensor voltages depending on excess air

A typical CO_e curve when slowly reducing O_2 and hence heading towards incomplete/bad combustion shows a significant increase of combustibles CO_e at the emission edge due to a lack of combustion air (also refer to Fig. 1).

In the excess air range in the case of clean, CO_e-free combustion, both sensor signals U_{S1} and U_{S2} are identical to each other and show the current percentage of oxygen in the exhaust gas duct according to Nernst. In the vicinity of the emission edge, however, the sensor signal of the second electrode U_{S2} rises disproportionally due to the cumulative non-Nernstian CO_e signal. For the locating of the emission edge, both the absolute sensor signals U_{S1} and U_{S2} and the relative sensor signal change according to time dU_{S2}/dt, i.e., the signal dynamics, especially of the CO_e electrode, are used.

O_2 CONTROL

To prevent the risk of an incomplete combustion, most industrial combustion plants are set to an air value λ with sufficient safety distance to the emission edge using classic O_2 control according to today's technological standards. Fig. 1 shows the resulting, nominal operating range, which can extend to $\lambda_{nom} = 1.3$ and beyond.

The safety distance to the emission edge must be selected to be larger, the greater the measuring inaccuracy and measuring error of the O_2 measurement, e.g., due to false air, and the greater and more dynamic the fluctuations are, especially in regard to changing gas quality. Depending on the process, this safety distance is necessary but unfavourably affects the efficiency since the optimisation potential up to the plant and fuel specific combustion optimum in the vicinity of the emission edge is not used.

The classic O_2 control adjusting to a constant O_2 value mostly compensates these fluctuations. With a load-dependent O_2 setting, the efficiency of the plant can be increased even further. Beyond the O_2 control, the emission edge strategy for combustion optimisation described in the following enables to settle much closer to the emission edge up to the operating point with maximum efficiency.

CO_e/O_2 OPTIMISATION (EMISSION EDGE STRATEGY)

For the locating of the emission edge, the fuel/air ratio is reduced dynamically towards a smaller air value λ without influencing the burner-firing rate until the CO_e sensor signal U_{S2} spreads from the O_2 signal U_{S1} at the emission edge (Fig. 4) and both the absolute sensor signal U_{S2} and the sensor signal dynamics dU_{S2}/dt increase significantly due to the incipient bad combustion. A small increase of the air value ultimately results in the optimum working point λ_{opt} of the system right in front of the emission edge. This cyclic procedure is repeated continuously in order to be able to guarantee operation close to optimum combustion, even in case of changed conditions or burner loads that lead to a shift in the emission edge.

Fast changes or disturbances in a plant that is already optimally set are detected immediately due to the permanent monitoring of the CO_e emissions. Additional system information regarding the current O_2 content in the exhaust gas and supplemental plausibility considerations may be used, if desired. Using these information, the plant will immediately be brought back into a "safe" operating mode with sufficient excess air and then, starting from a safe characteristic curve using the routine described above, led up to its optimum operating point under the changed conditions again.

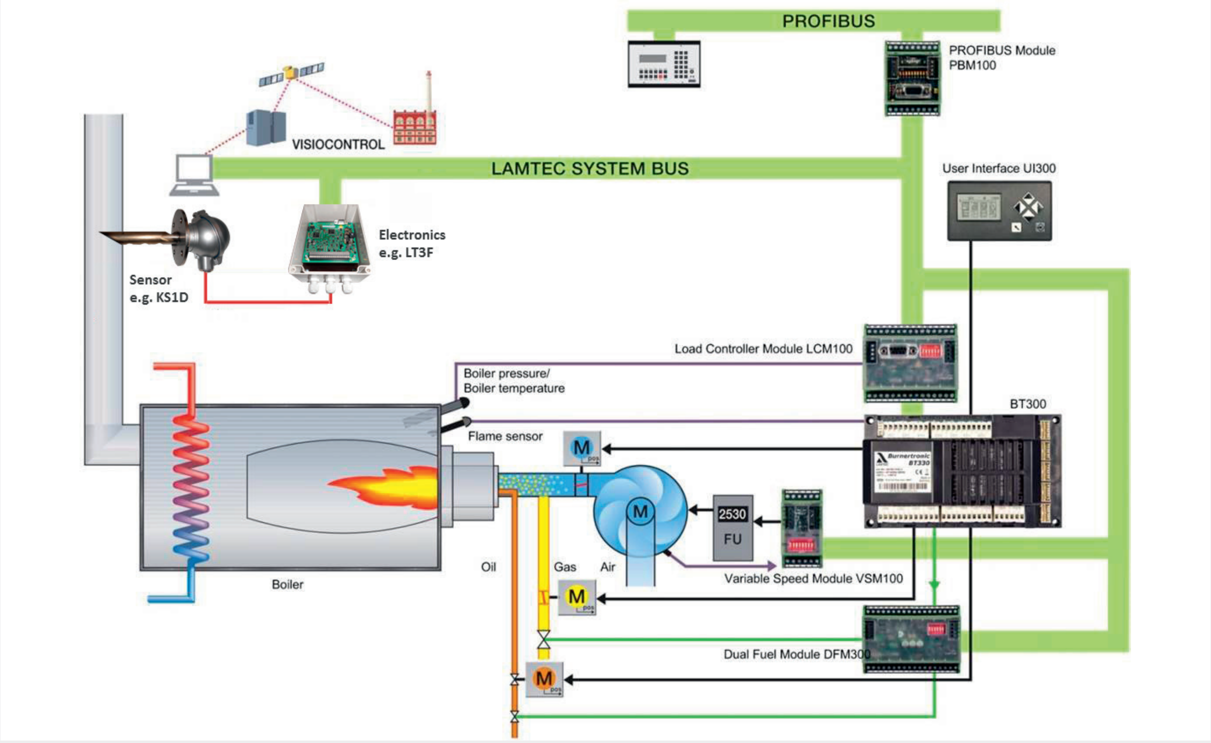


Fig. 5: Boiler with dual-fuel burner equipped with BurnerTronic BT300, speed control, in-situ gas sensor and sensor electronics for optimise CO_e/O_2

The CO_e/O_2 optimisation has been used successfully worldwide for over 10 years. The most important advantages of the CO_e/O_2 optimisation in comparison with an O_2 control are as follows:

- Higher energy savings through continuous self-optimisation in every load point,
- Better control performance through significantly shorter setting times,
- Independent of false air,
- Failsafe,
- Robust,
- Maintenance-free.

SAVINGS CALCULATION

For combustion control, a complete range of electronic burner control devices, fuel/air ratio controllers, IR/UV sensors, flame monitors, and CO_e/O_2 measuring devices with the pertinent sensor systems is available on the market.

For medium-sized plants from 0.3-5 MW, the BurnerTronic BT300 is the first device worldwide in its price class that can be used for both O_2 control and CO_e/O_2 optimisation (**Fig. 5**). It combines all advantages of an electronic fuel/air ratio control with an electronic burner control device. Since the market introduction about 3 years ago, more than 3,000 plants per year and rising have been equipped and

Table 2: Conservative savings calculation for the modernised 5 MW dual-fuel burner in Fig. 6

Savings for burner 1:		Low load	Medium load	High load	
Operating hours	h/a	800	800	6,400	
Fuel costs (assumed)	€/h	46	105	159	
O_2 reduction through O_2 control	Vol.%	1.28	1.46	1.33	
Savings through O_2 control	€/a	464	1,223	13,598	15,286
Additional O_2 reduction due to CO_e/O_2 optimisation	Vol.%	0.33	0.22	0.33	
Additional O_2 reduction due to CO_e/O_2 optimisation	€/a	120	186	3,353	3,660
Savings due to speed controlled fan	€/a				2,974
Total savings	€/a				21,920

Fig. 6: 5 MW dual-fuel burner converted for CO_e/O_2 optimisation with LT3F sensor electronics and switch cabinet with integrated BT300, speed control, etc.

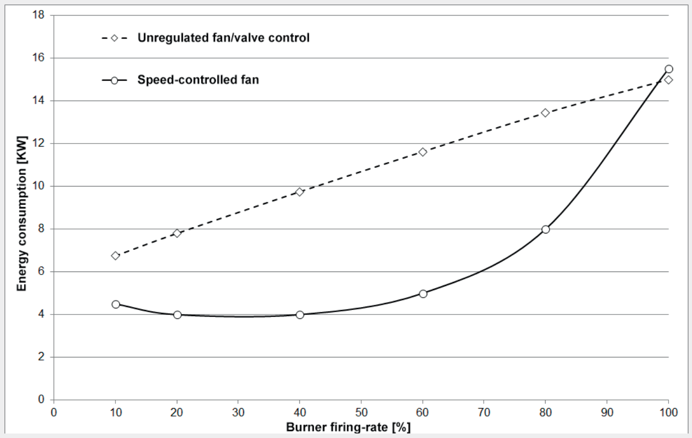


Fig. 7: Comparison of the energy consumption of the unregulated and speed-controlled combustion air fan via the burner load

optimally operated with this component – for the sake of a clean environment!

Fig. 6 shows one of the boilers of a thermal processing plant for the food industry with a 5 MW dual-fuel burner (oil/gas). All boilers of the plant were recently equipped with a CO_e/O_2 optimisation and a load-dependent speed control of the combustion air fan. To estimate the profit of the conversion measures, the plant and operation specific boundary conditions and some of the measurement data from before and after the conversion are included in the savings calculation.

As a boundary condition, typical fluctuations according to Table 1 are included in the savings calculation. The exhaust gas temperature was measured at 150 °C at high load and at 120 °C at low load. The combustion air temperatures typically lie at 35 °C in the summer and at 10 °C in the winter. To calculate the savings, fuel costs of € 0.35/ kWh_{gas} are assumed.

Through the use of a speed-controlled combustion air fan instead of a fan with valve control operated at constant speed, an additional saving in electrical power is achieved according to **Fig. 7**. For the calculation of the electrical savings, energy costs of € 0.12/kWh_{el} are assumed.

In **Table 2**, the results of the mostly conservative savings calculation based on the well-known Siegert formula are briefly introduced. According to this table, the annual savings due to O_2 control reach up to € 15,286 for each boiler of this plant. The additional gain due to CO_e/O_2 optimisation amounts to € 3,660. The CO_e/O_2 optimisation using a single probe (KS1D) is an additional benefit and comparable with a pure O_2 control in regard to expense. For this reason, it is easy to use for all plants, increasingly of interest for boilers with medium-sized output, and recently available as well. The savings due to speed control amount to another € 2,974 per year. This results in a total savings of € 21,920 a year per boiler! In addition to these fuel or cost savings for plant operators, the environment also benefits from an annual CO_2 reduction of about 130 t per boiler in this plant.

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