Taking full benefit of oxygen sensors & automatic control

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Since more than 20 years STG has been active in production, installation and services for oxygen sensor applications to the glass industry. These sensors became a common standard with a service lifetime of about 3 years, best results up to 8 years, applicable up to 1500 °C, applicable even under highly reducing atmosphere, providing a signal good for reliable measurement and good for automatic control. About 10…20% of the applications are really using them for automatic control.

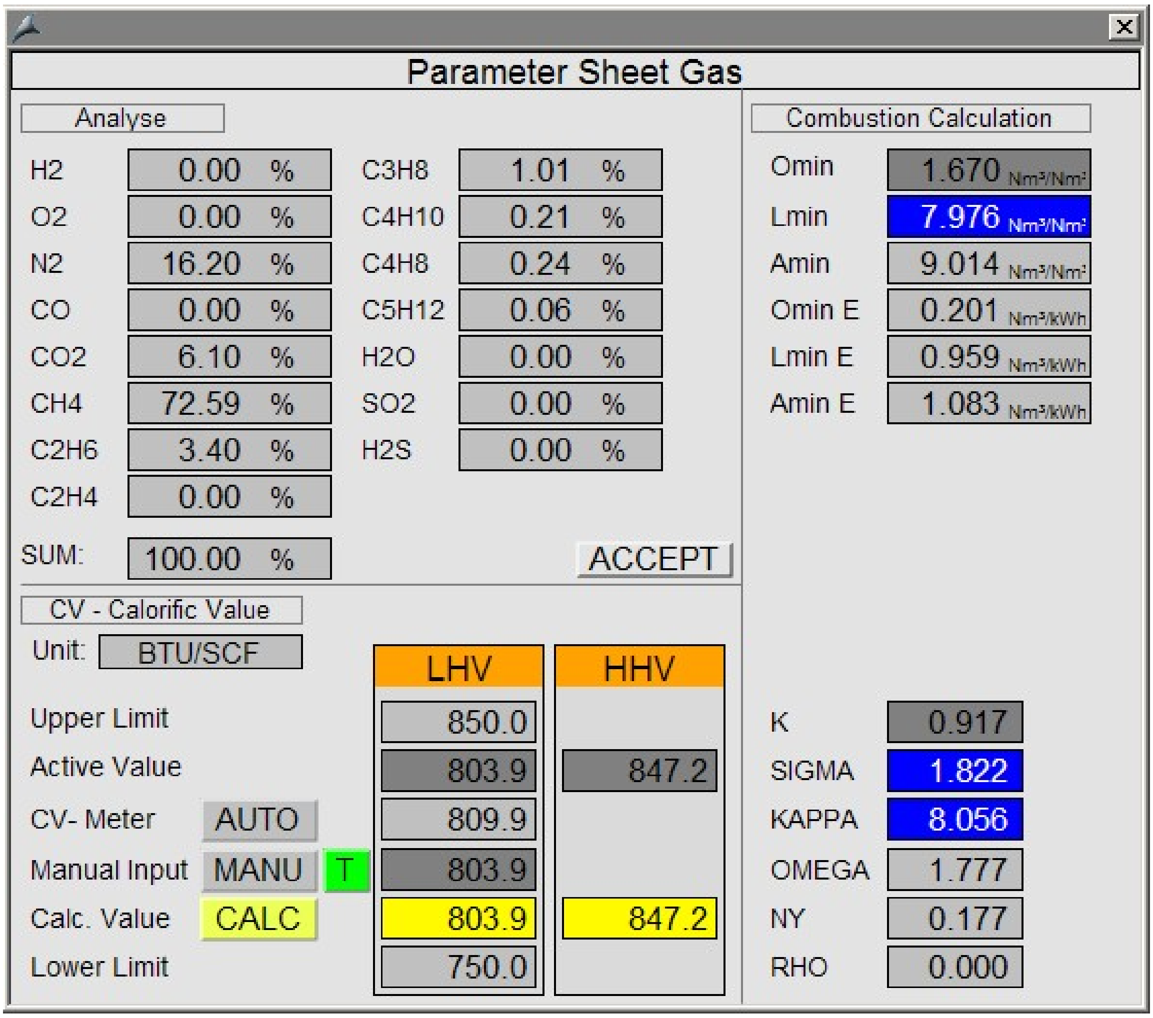
Picture I: Oxygen sensor in regenerator crown installation

We install them typically in the regenerator crown in vertical position – which gives better service life and never gives any problems with measuring accuracy due to this position.

All this would not be a reason to come over the ocean for giving this paper.

New developments are really going on in the signal processing of these sensors, in the answer to the question – which value can such sensor give you?

Oxygen sensors give you much more information than oxygen percentages only.
Combined with the information about fuel composition – may be gas or oil or both in a mix – the system can make the full combustion calculation.



Picture II: Natural gas analysis as a basis for PLC-integrated combustion calculation

Another point to be observed is the gas composition. With our experiences the gas composition is not constant. If Calorific value varies – so stoichiometric air demand and dimensionless gas parameters K, SIGMA, KAPPA etc. will be vary as well.

If you have available an actual process value of natural gas calorific value, so the software block shown in picture II will adjust the key figures accordingly.

Based on the actual gas composition, the signal processing provides the amount and the composition of flue gas.

Providing CO percentage requires some more comment.

We get from sensor voltage not only Oxygen percentage, but based on Boudouard chemical balance the CO percentage corresponding to O_2% - in chemical balance only. This is the basis to get the Lambda excess air value

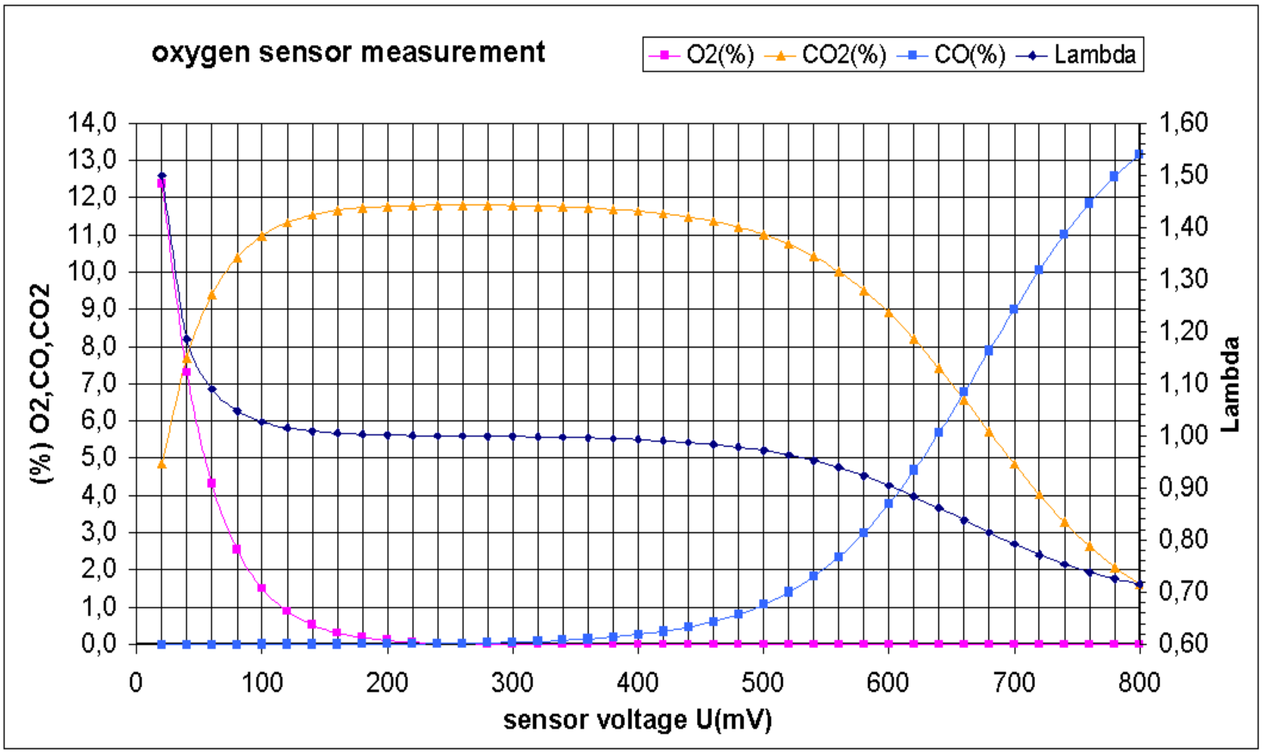
$$\lambda = 1 + \frac{0{,}2094 * (\kappa + \omega + Ge) - 0{,}7906 * \psi}{\sigma} * \frac{[O_2\%]}{20{,}94\% - [O_2\%]} - \frac{\psi}{\sigma}$$

Using abbreviation as

(D_46) $$\psi = \frac{(1 + Ge) * RaCO}{2 * (1 + RaCO)}$$

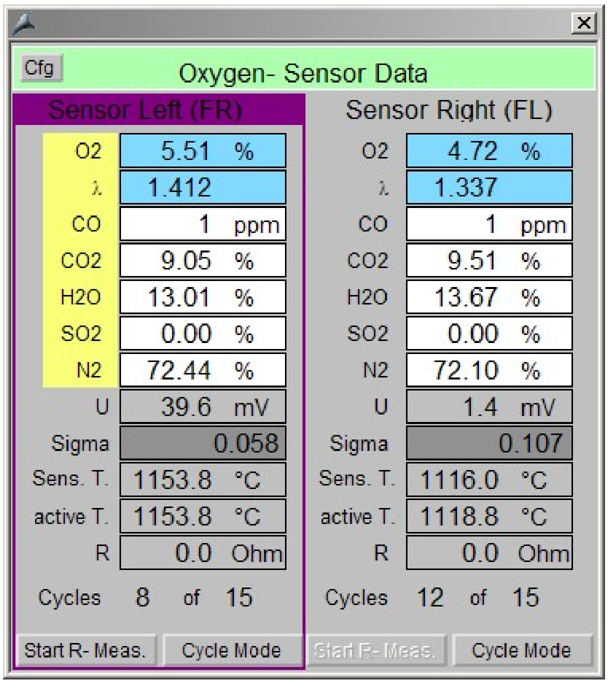
notice: 20,94% is oxygen percentage in oxidant (air) O_2% in Vol.%
79,06% is nitrogen percentage in oxidant (air) N_2 in Vol.%

Oxygen sensor signal processing will not give you any CO temporarily exceeding the chemical balance figures due to turbulent combustion – but it gives you reliable information how much excess air or how much air is missing in the giving combustion.



Picture III: Oxygen, CO and Lambda as a function of sensor voltage for given temperature and for given natural gas composition

Roughly to say: For sensor voltage U < 200mV sensor primarily indicates you Oxygen percentage, CO is quite low – in chemical balance.



Picture IV: Indication of flue gas composition, Lambda value and Sigma turbulence indicator

But going further into reducing situation, we see sensor voltage increasing more and more up to 800 mV, where Oxygen is more or less no more measurable, but in this area U >200mV sensor voltage primarily becomes an indicator for increasing percentage of CO.

Lambda excess air figure is available over the full range of sensor voltage, indicating oxidizing and reducing conditions as well. Please notice, that Lambda is a real process value, representing the status of total air which was available for the combustion. To get it we need just only the sensor voltage, temperature and fuel composition.
Picture IV: Indication of flue gas composition, Lambda value and Sigma turbulence indicator

Sigma here represents the standard deviation of sensor voltage – divided by the average of the voltage – to be used as an indicator for the turbulence of combustion, which becomes interesting based on the general knowledge, that the less turbulent the combustion is, the better will be efficiency and low NO_x results.

Now let us come to the most interesting point: sensor application for automatic control.

Lambda excess air value is much better qualified for automatic control function, than oxygen percentage is. This is due to two reasons:

a) Lambda value covers whole scope of possible sensor voltage, oxidizing and reducing combustion by same algorithms and same way of control

b) Lambda is in a linear relationship with combustion air – therefore any required difference in Lambda may be directly converted into required modification of air flow, without waiting for the response of the combustion system

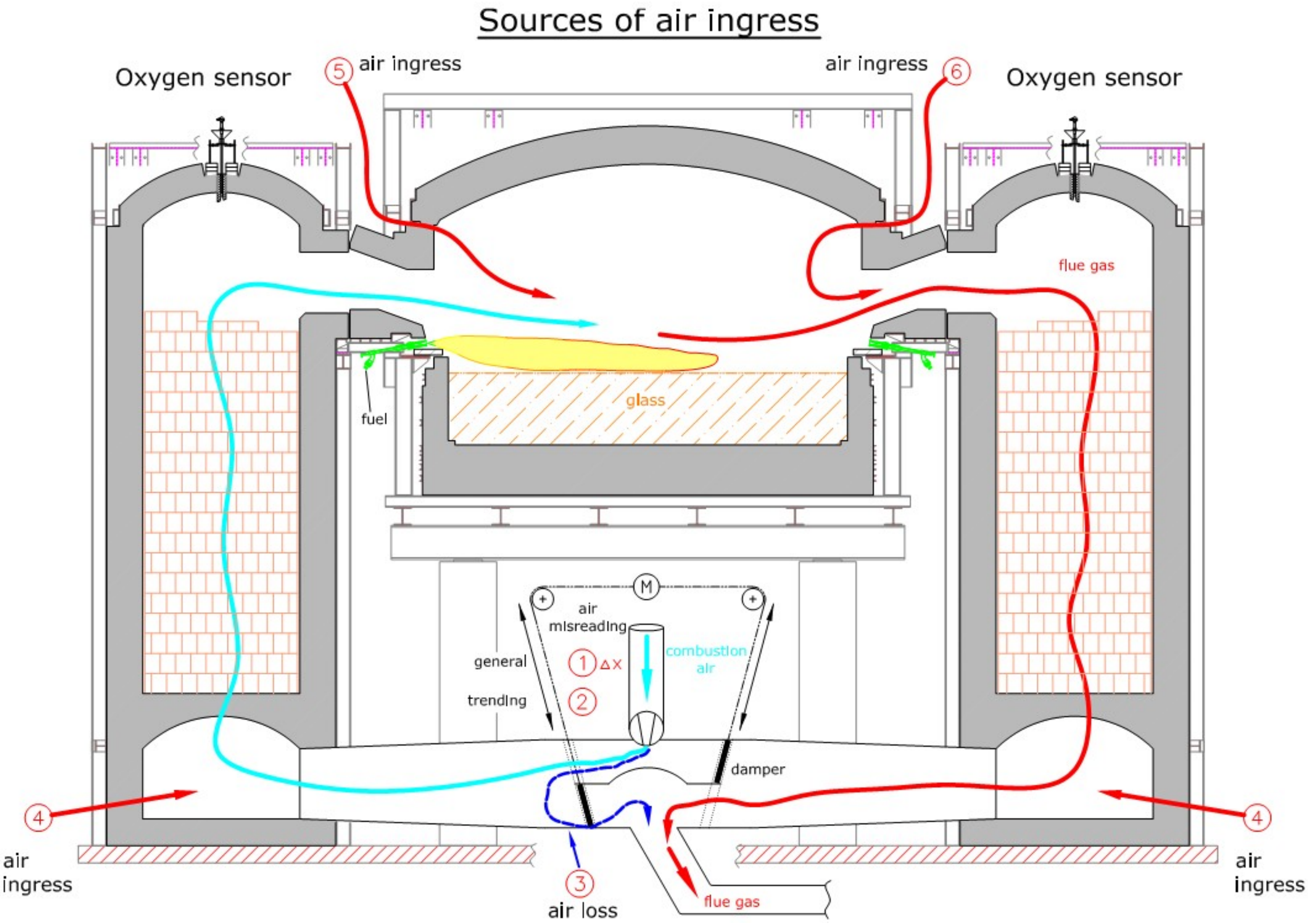
Lambda process value PV_Lambda gives us the amount of uncontrolled air or ingressed air PV_XF as:

$$PV\_XF = PV\_Lambda * LMIN * PV\_fuel - PV\_comb.air$$

(LMIN = stoichiometric demand of air)

Uncontrolled air XF is the major concern of automatic control – we call it Lambda Control. Lambda Control means:

- Monitor ingressed air
- Minimize ingressed air
- Indicate ingressed air's source
- Compensate ingressed air – whatever is not avoidable and whatever is acceptable to compensation



Picture V: Sources of uncontrolled air XF

There are different sources of uncontrolled air – requiring different control strategies to compensate or to deal with:

(1) General misreading of combustion air measurement "appears like" uncontrolled air – is not critical, but better to find out by comparison of two or more operation points at different fuel flow

(2) Drifting misreading of combustion air flow – comes with an increasing amount of "hidden air" and this is fully correct to be seen and compensated as air ingress

(3) Loss of combustion air – air flow short-circuit caused by incompletely closed reversal damper – gives a negative air ingress and can be identified by typical trending behavior. Air loss is typically increasing over the duration of firing period – so oxygen reading gives a falling trend

(4) Air ingress into regenerator bottom where the lowest pressures are on the combustion air side – is a typical air ingress and can easily be compensated by modification of combustion air flow.

(5) air ingress into furnace chamber not taking part in heat up in the regenerator or even

(6) air ingress into furnace chamber even not taking part in combustion

Any uncontrolled air of types (1), (2), (3) or (4) can be fully compensated by modification of combustion air flow where the new setpoint is given by:

SP_Air = SP_Lambda * LMIN * MAX(PV_fuel, SP_fuel) – XFA

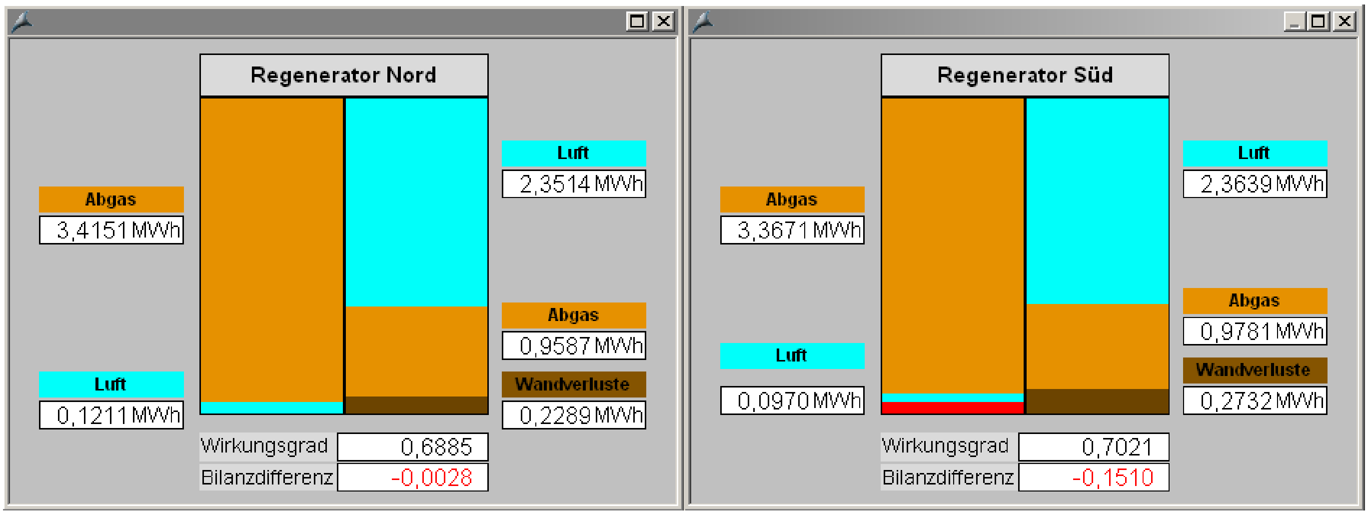
Where XFA is a figure for the ingressed air, but using not just the actual process value, better taking in account the typical trending patterns of the last 5 reversal periods.

Compensating any ingressed air of types (5) and (6) – entering into furnace chamber – will risk to disturb thermal balance of regenerators and can be done in close limits only.

Therefore it becomes an important point, how to make a difference between air ingress into bottom of regenerator or hidden air from combustion air misreading on the one side – and air ingress into furnace chamber on the other hand.

Answer is: we use the temperature footprint of ingressed air in the regenerators, to identify whether it can be compensated by modification of ingressed air or not.

There is a software block to check on-line energy balance of the regenerators:



Picture VI: On-line energy balance of regenerators

The different types of ingressed air have different impact on the energy balance of regenerators:

Type (1) and (2) affect both firing sides in the same way and can be compensated by modification of combustion air without any affect to the energy balance of the regenerators.
Type (3) and (4) of uncontrolled air – air loss or air ingress into regenerator bottom – will have an effect different between the firing sides – and compensating them by modification of combustion air will just improve thermal balance of regenerators – providing finally same temperatures at both regenerator crowns.
Worst cases are type (5) and (6) of air ingress – stealing energy from the furnace and disturbing thermal balance of regenerators. Any effort to compensate direct air ingress into furnace will result in a further disturbance of thermal balance of left and right regenerator and is very likely to increase regenerator temperatures, which is again not a welcome result.

The only way out is: seal the furnace and increase furnace pressure.

So conclusion is: Identify ingressed air, make it a “normal” process value.
Compensating it by modification of combustion air flow works perfectly as long as the reason of air ingress is anywhere in regenerator bottom or upstreams of regenerator. In these cases compensation even will improve thermal balance of regenerators.

Compensating of ingressed air entering directly into furnace chamber disturbs the thermal balance of regenerators and cannot be done by modification of combustion air – or at least only in very close limits – increase of furnace pressure is the more reasonable way.

This is what we call “the temperature footprint of ingressed air”

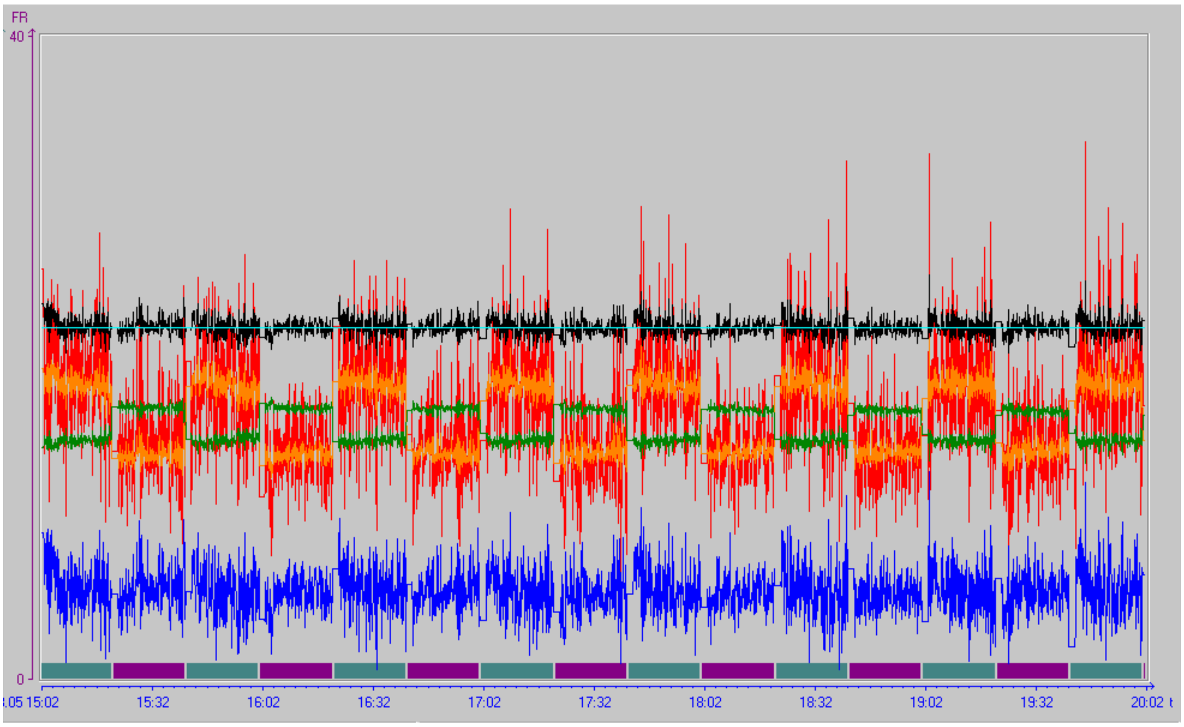
Compensation of ingressed air by modified combustion air works perfect in most of the situations. But we have to accept, that there are situations, where it cannot work – just when it would be disturbing thermal balances and increase regenerator temperatures.

Practically we use an automatic control of thermal balance of regenerators, playing actively – but in limits – with a shifting time between left hand side and right hand side firing period to transport heat from the hotter to the colder regenerator in order to get same temperatures or better – in order to get same amount of preheated air energy flow into furnace from both regenerator sides.

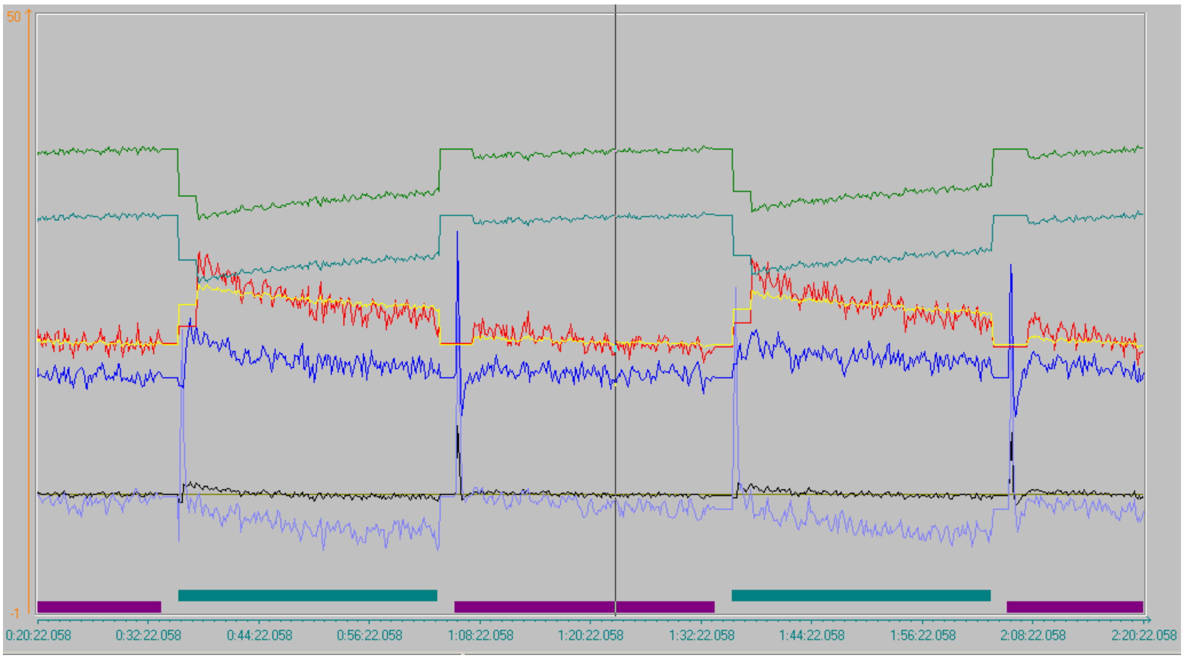
All these are slow control processes. Balancing the regenerators may take days, even a week when starting from an unbalanced situation. Later on shifting time comes down to nearly zero – which indicates that compensation of ingressed air is correct without disturbing the thermal balance of regenerators.

Or: Over days and weeks it will be found that balance controller requires a more or less stable difference between left side and right side period – indicating that there is a continuous reason for thermal unbalance of regenerators, resulting eventually from ingressed air into furnace compensation. In such situation, an increase of furnace pressure should help to reduce ingressed air and to improve thermal balance of regenerators.

Showing how a well functioning Lambda Control should be working:



Picture VII: Lambda Control at an endport furnace
(red = ingressed air, yellow XFA to compensate, dark blue is oxygen O2%
black and clear blue Lambda PV and SP, green is ratio slightly different left and right)



Picture VIII: Lambda Control at a crossfired furnace having 2 air flow control groups
(red = ingressed air, yellow XFA to compensate, dark & light blue is oxygen O2%
black and clear blue Lambda PV and SP, green1&green2 is ratio slightly different left and right)

Picture VIII is showing Lambda Control for a cross-fired furnace, having 5 ports and only 2 oxygen sensors and 2 groups of air flow control.

Lambda Control has to take care for the neighboring ports also, with no oxygen sensors, calculating limits to consider the eventually hidden risk of too low Lambda value on one of the neighboring ports.

The diagram shows decreasing trend patterns of ingressed air and oxygen – resulting in increasing trend patterns of ratio, especially for left fire (see fire side indication on bottom line) which indicates a possible air leakage of reversal dampers for left fire.

Conclusion:
Lambda Control has become a tool worth to be used for efficient furnace operation. We have learned to "read" indications of misreading and air losses, we have learned carefully to see not only oxygen sensor results but also the temperature footprint of ingressed air. And we know that there are limits also for the compensation of ingressed air by modified combustion air – limits set by the requirements of thermal balance of regenerators and furnace pressure.

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