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AUTOMATIC EXCESS OXYGEN CONTROL IN STEEL REHEATING FURNACES

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Key words: control, oxygen, TDLAS, reheating, spectroscopy, laser, furnace, iron and steel industry

SUMMARY

This project investigated a new technique for automatic control of the excess air and oxygen in steel reheating furnaces using tunable diode laser absorption spectroscopy (TDLAS). These instruments measure in-situ, average gas concentrations, which makes them suitable for process control. Several trials have been made with 2 commercial TDLAS oxygen analysers (from Siemens and NEO). Both instruments gave good average oxygen concentrations across the furnaces, but combined temperature and oxygen measurements were associated with problems. Automatic excess oxygen control was successfully proven in a pilot trial at MEFOS, but instrument problems delayed industrial trials of the technique.

TDLAS for gas analysis and temperature sensing offers steel hot rolling mill the opportunity to improve their reheating furnace control. Potential benefits include lower energy consumption, less scale losses, and more uniform furnace operation for less off-grade production and higher product quality.

Potential energy savings of 72 GWh/year were estimated based on a reduction in scale losses and an increase in furnace efficiency, assuming the technique is implemented for the reheating of 5 Mton/year of steel. The expensive diode laser failed twice in the Siemens instrument tested, which resulted in a long delay for repairs, and a replacement laser with too weak of a beam for the hot

zones of the furnace. Laser technology is advancing quickly, so these benefits assume the problems experienced are only a temporary setback.

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1 INTRODUCTION AND THEORY

Zirconia based oxygen analyser have been marketed for many years as a means of better process control in a variety of furnaces, including steel reheating furnaces. There have been a variety of problems associated with zirconia sensors (see chapter 3 - Excess oxygen control), so that oxygen analysis is still primarily used for process monitoring instead of automatic process control. A new technique for gas analysis “tunable diode laser absorption spectroscopy” (TDLAS) has been commercialised recently, and TDLAS has some advantages over zirconia based gas analysis. This report summarises research on this optical technology.

Optical spectroscopic techniques are used in extraction type optical gas analysers which have been on the market for decades. There are many different types of systems all based on Beer-Lambert's absorption law:

”Light absorption is a function of the gas concentration in the path of the light beam”.

Two general categories are based on the wavelengths used: Infrared (IR) or Ultraviolet (UV). Different gases absorb at different wavelengths, so the peak intensity for a given gas can be related to the concentration of the gas. Instrumentation/ analytical techniques are used to relate the absorption of the gas of interest at specific wavelengths to the gas concentration. These instruments have high maintenance costs associated with sample extraction and preparation, plus they only give a point analysis like conventional zirconia oxygen analysers, so they are not normally used for combustion control. DIS (Dispersive Infrared Spectroscopy) and FTIR (Fourier Transform Infrared Spectroscopy) are used with extractive type sampling. DOAS and TDLAS systems are being marketed in Sweden for in-situ gas analysis, which is of interest for controlling reheating furnaces. A comparison of these 4 methods is given below.

1. DIS: Dispersive infrared spectroscopy (example: Perkin-Elmer Model 237B Infrared Spectrometer)

DIS is an old technique for gas analysis using optical spectroscopy. A hot body such as a Nichrome coil or a SiC plug supplies a beam of IR radiation which is split to pass through the sample gas and the reference gas. A monochromater is used to split the beam into various wavelength bands which then are recorded by the detector. The monochromater can use a grating and a mechanical slit to select certain wavelengths for detection. The detector can be a thermal detector (thermocouple or thermister) or a photon detector (semiconductor device) [1].

2. FTIR: Fourier Transform Infrared Spectrometry (example: Nicolet Magna-IR 750 FTIR)

A FTIR instrument uses an IR source, interferometer and a detector. The radiation source can be similar to DIS. The interferometer splits the IR beam and generates an interference pattern by varying the path length before recombining the beams. Typi-

cally a Michelson interferometer is used in which the light is split using a fixed and a moving mirror. The recombined beam is passed through the sample gas and then to a detector. The resulting curve of absorption intensity versus time due to the movement of the mirror is converted by the Fourier transform into an intensity versus frequency spectrum. A fast detector is needed like the MCT semiconductor detector. A FTIR instrument is faster and more sensitive than DIS, for example, 1 s in a FTIR instrument versus 10 min in a DIS for the same signal to noise ratio. A stronger beam is used, since a slit which reduces the beam is not required, so the beam area can be 100 times larger. Simpler mechanical design gives less wear and improved reliability, plus external calibration is not required [2].

3. DOAS: Differential Optical Absorption Spectroscopy
(example: OPSIS system 400)

The DOAS method uses a broad spectrum light source, for example, Opsis uses a xenon lamp, to measure the concentration of many gas components with the same instrument. A wavelength versus intensity spectrum is recorded, then the spectrum is treated to remove the zero gas spectrum and other slowly varying factors as dust. A differential absorption spectrum is then formed by taking the logarithm of the curve. A computer program then finds the gas concentrations that best match the peak heights obtained. A standard deviation for the resulting gas concentrations can be obtained from the deviation between the predicted and the measured peak height. The wavelength range can be selected with detectors for ultraviolet (UV, for example for NO and NO2) to infrared (IR, for example for H_2O and CO_2). [3]

4. TDLAS: Tunable Diode Laser Absorption Spectroscopy
(example: AltOptronic LDS3000 and NEO LaserGas O_2 monitor)

A laser diode is tuned to the wavelength where the gas being measured absorbs light. The intensity of the absorption peak is then related to the gas concentration measured using a reference cell for comparison. The intensity of the absorption peaks can have different temperature sensitivities, so the process temperature can be deduced when 2 or more absorption lines are present by calibrating a curve of the intensity of the peaks versus temperature. Laser light frequency depends on the composition of the semiconductor, so that the wavelength can be set for various gases. There is a slight change in wavelength with the current through the diode which is used to scan the light through the absorption peak [4]. This temperature sensitivity for oxygen absorptivity and the effect of temperature on gas concentration from the ideal gas law require accurate gas temperatures for accurate oxygen concentrations.

Both DOAS and TDLAS allow in-situ measurements, but the TDLAS method is simpler and therefore it can be less expensive than DOAS.
Advantages of TDLAS include:

- Multiple sampling points possible with fibre optics cables.
- An average gas analysis in the path of the beam is better suited for burner control than point analysis.
- Fast response time (< 2 s) with in-situ sampling, and the fast response can be trade off against higher resolution.
- Low maintenance costs with non-extractive sampling (3-month intervals).
- High accuracy in measurements ($\leq$ 0.1 % O_2).
- No moving parts to wear, break or plug.

Disadvantages of TDLAS include:

- Higher cost than for point analysis with zirconia probes.
- Purging with N_2 is needed when measuring low O_2 concentrations.
- Short O_2 laser operational lifetimes.
- Developmental/operational problems with new technology.
- External gas temperature measurements are required for conditions when TDLAS cannot measure internally.

Direct measurements of the peak heights lead to the need to resolve a small change in a large signal, therefore two different methods of modulation have been developed in TDLAS: Wavelength Modulation Spectroscopy (WMS also called Derivative Spectroscopy) and Frequency Modulation Spectroscopy (FMS). These give a zero baseline and avoid laser noise. Modulation typically uses 50 kHz with 100 kHz detection at the second harmonic in radio wavelengths. A current with this frequency is added to the driving current of the laser as it is tuned or varied across the absorption line [5]. An alternative is FMS in which a higher frequency (typically about 100 MHz) is used than with WMS (about 50 kHz), but with the same purpose, that is, to modulate the laser frequency and generate a derivative absorption profile at the peak for the gas being analysed.

The advantage of both the DOAS and TDLAS instruments is the availability of instruments that can be used for in-situ gas analysis. Table 1 gives a comparison of the two techniques. Note that direct oxygen analysis is not normally done with DOAS, since the DOAS technique has poorer accuracy than the TDLAS technique for the relatively weak oxygen peaks in the NIR spectrum.

Table 1. Comparison of DOAS and TDLAS.

Factor	DOAS	TDLAS
1. Number of gases	Several	One per sensor
2. Oxygen analysis	Indirect from CO2 and H2O	Direct
3. Dust sensitivity	Some	Little
4. Accuracy	Linearity <±1 vol % range for H2O with 0-30% min range	±0.1 vol% O2
5. Temperature measurements	No	Yes
6. Wavelengths	UV to IR	NIR (i.e. 760 nm for O2 or 1 543.7 nm for H2O)
7. Recommended path	0.5 to 10 m	1-10 m
8. Light source	Xenon lamp 150 W	Laser diode (<1 W)
9. Temperature tolerance	-40 to 50C	-20 to +55C
10. Max. furnace temperature	No restriction	1500C (NEO)
11. Noxious gases	NO, NO2, SO2	NOx (NEO)
12. Analysis of additional gases	Software change, if in the same range (UV or IR)	New emitter/detector

The laser beam should traverse the furnace where combustion is nearly complete so that an average oxygen concentration can be obtained for all the burners in the burner control zone of interest. Figure 1 is a top view of a furnace burner zone showing a possible method for monitoring combustion of 5 burners (oval flames).

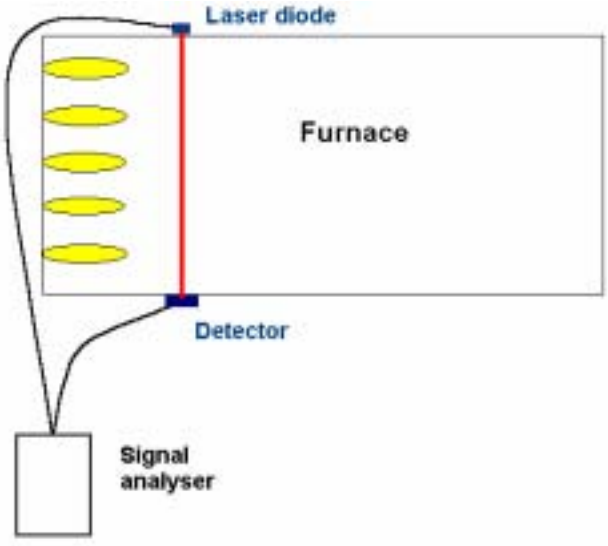

Figure 1. A sketch of how a measurement system using TDLAS can be configured.

2 TRIALS WITH TDLAS

This project began with industrial trials using a Siemens LDS3000 TDLAS, since the rolling mill (SSAB) was willing to financially support trials directly, and the costs to the project are lower than for pilot trials.

2.1 Industrial trials at SSAB

2.1.1 Trials Oct-Dec 2000 with Siemen's LDS3000

The industrial trials at SSAB Tunnplåt, Borlänge were first made with a LDS3000 from Siemens Laser Analytics (formerly AltOptronics) [6]. Later trials were also made with the Laser Gas O2 Monitor from Norsk Elektro Optikk A/S (abbreviated as NEO) [7]. Holes were drilled in the walls of furnaces 301 and 302, so that the instruments could be mounted on the furnace walls with the beam passing across the width of the furnaces. Zone 1 (first heating zone) and zone 5 (soaking zone) were monitored in furnace 302 which is oil fired, while only the soaking zone was monitored in furnace 301 (gas fired). NEOs instrument measured only the oxygen concentration and it was only tested in zone 1, without problems. Siemens TDLAS has 3 channels, so two channels were used in furnace 302 and one channel in 301. A zirconia probe and the use of two measurement points gave more information from furnace 302 than 301, so most of the data presented is from furnace 302. A side view of furnace 302 with the measurement points is given below. Good beam alignment is important, so a Siemens representative helped with the initial installation. Stable mounting brackets on the furnace walls and alignment with a hot furnace gave good results, and little maintenance was required during the trials, which lasted several weeks.

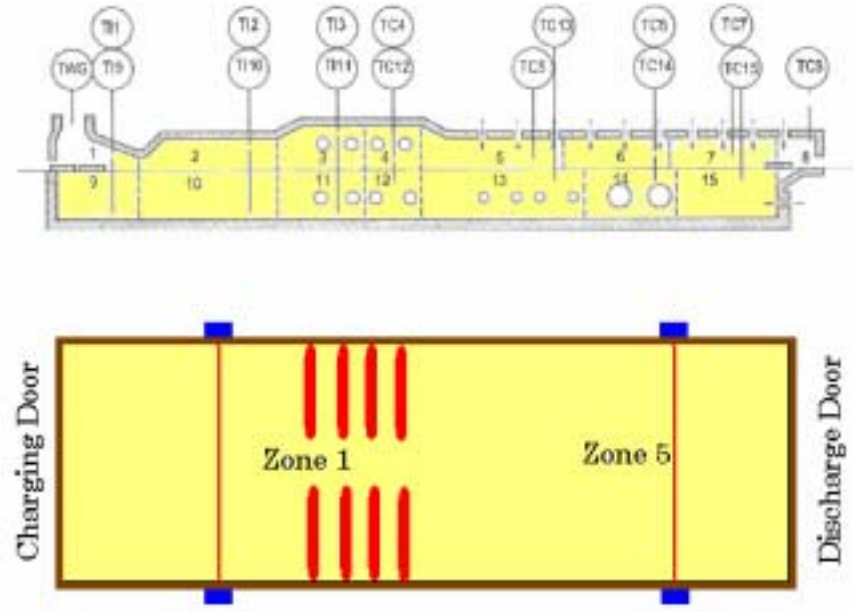

Figure 2. A side view of furnace 302 at SSAB, with a diagram of the placement of the laser sensors.

Initially, the results looked promising from furnace 302. Both the gas temperature and oxygen concentration in zone 1 were generally reasonable, even for relatively long periods as for Oct 26th in Figure 3 below, with only a few fast spikes in the data that presumably could be filtered away with time-averaging techniques.

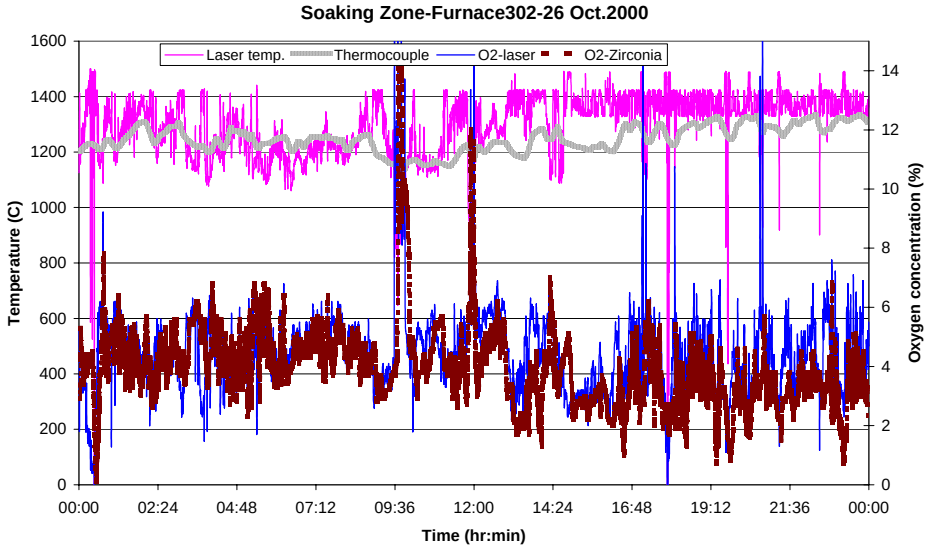

Figure 3. Relatively stable temperature and oxygen concentration measurements with TDLAS in zone 5 on Oct 26th.

Sometimes there were many peaks with unexpectedly high gas temperatures (2000 °C or full scale) dropping rapidly to zero in zone 5 together with large, fast oscillations in oxygen concentration (for example, about 0-4 % oxygen at about 9.00 on the 28th of October in Figure 4 below). The furnace gas temperature cannot physically suddenly jump up and down between 2000 °C and 0 °C, so there is a problem with the instrumentation. This problem was investigated in later pilot trials, and the cause is insufficient intensity or magnitude for the absorption peaks. The instrument is simply outside its operating range for measuring both the oxygen concentration and the gas temperature. The minimum oxygen concentration is temperature dependent, but greater than about 5 % oxygen at about 1600 °C worked fine (which on a 12 m path length gives 60 %-m).

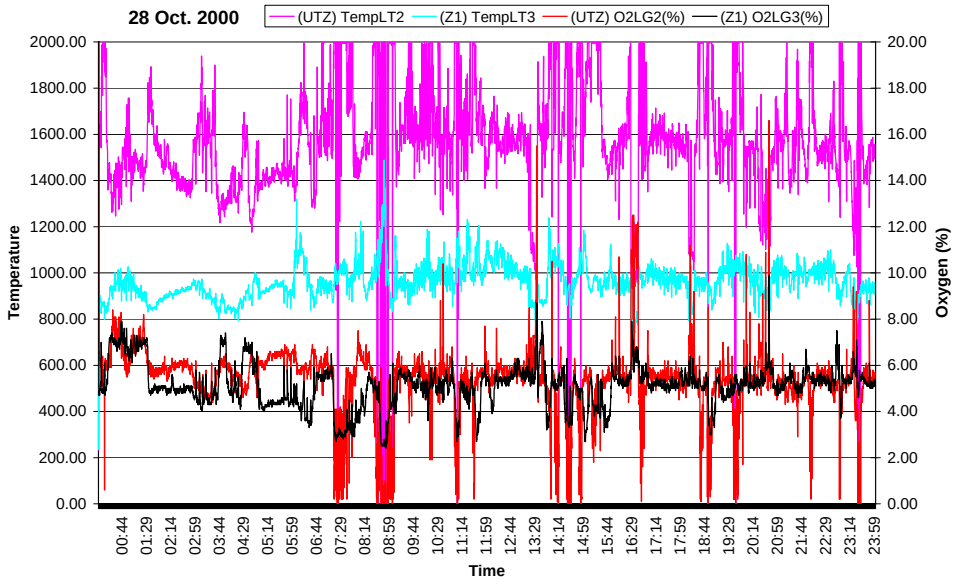

Figure 4. Large oscillations in gas temperature and percent excess oxygen when the oxygen concentration dropped too low for combined measurements.

Enlarging the time scale (fewer data points) and including the zirconia oxygen measurements shows a large discrepancy between the TDLAS and point measurement. One can question the accuracy of the oxygen measurement data with gas temperatures at 1600 °C or more. There was an apparent drop in the gas temperature to 1100 °C, and both oxygen measurements correlated quite nicely at about 6 %. Gas temperatures are uncertain when the oxygen concentrations are uncertain, and vice versa, since the two measurements are interlinked in this first trial. Higher sensitivity for oxygen analysis is possible with an external gas temperature, which was tested in later trials.

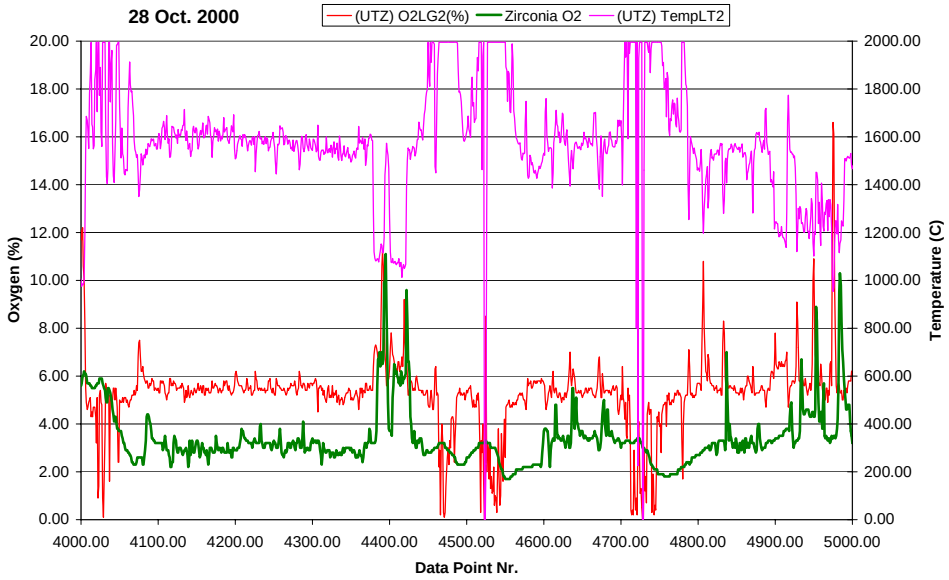

Figure 5. Discrepancy between O_2 data from the ZrO_2 and TDLAS probes.

A x-y plot of the oxygen data shows the zirconia to generally record a higher oxygen concentration when the TDLAS had a low value, and the reverse. The oxygen level measured by the TDLAS was higher than the zirconia data at moderate oxygen concentrations (about 6 %). The minimum oxygen concentration for accurate combined temperature and oxygen measurements at 1600 °C is therefore uncertain.

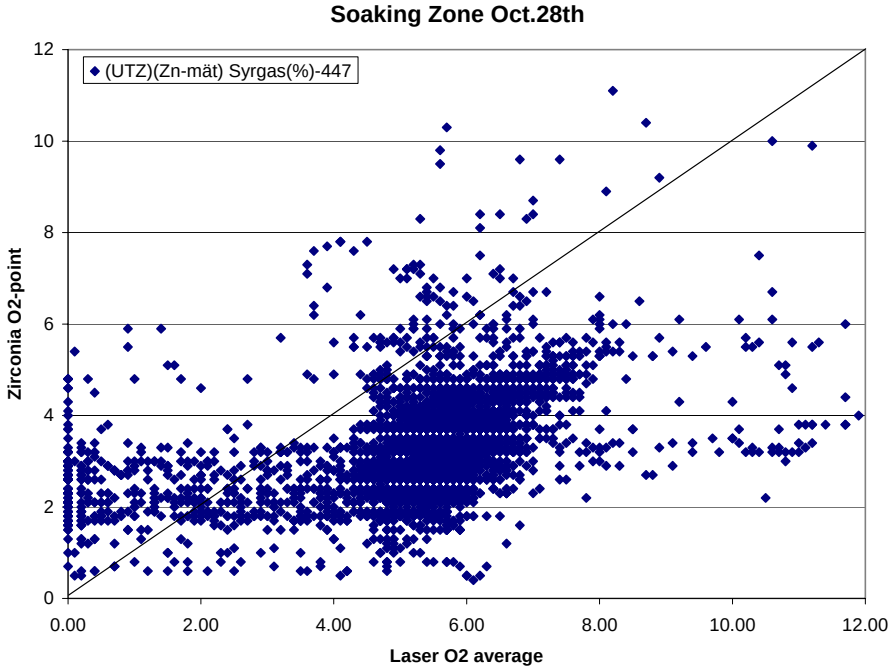

Figure 6. Plot of the zirconia point oxygen measurements versus the average oxygen concentration with the TDLAS in the soaking zone.

The large temperature swings in the soaking zone on October 30th are shown with an enlarged time scale in the figure below. Note that with the lower gas temperatures (with a 1250 °C wall temperature) the oxygen concentration can drop to about 3 % without problems (or 36 %-m), but about 1 % oxygen or less (or 12 %-m) could give problems. The percentage oxygen measured at a point with the zirconia sensor versus the average from the TDLAS could have a large disagreement expressed as a ratio between each other. This is a major argument for the use of TDLAS for controlling to low oxygen concentrations. Zirconia sensors could provide adequate accuracy for relatively high oxygen concentrations, as in the preheating zone, but point measurements can give relatively large errors at near stoichiometric combustion (that is, ± 1 % O_2 is ± 25 % error at 4 % O_2, but ± 100 % error at 1 % O_2).

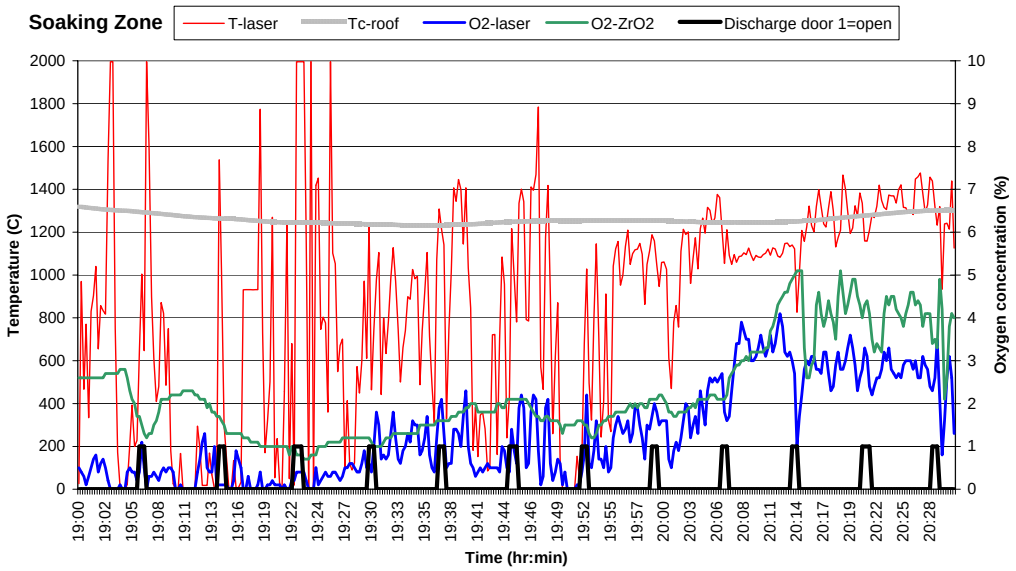

Figure 7. Unstable conditions in the soaking zone on October 30th, showing also the large discrepancy possible between point and average oxygen measurements at low oxygen concentrations.

The same problem with unstable gas temperatures occurred for furnace 301 firing propane instead of oil. The figure below shows how that 4 % oxygen with a gas temperature of 1400 °C gave stable measurements, but the lowest oxygen concentration is difficult to see with this diagram scale.

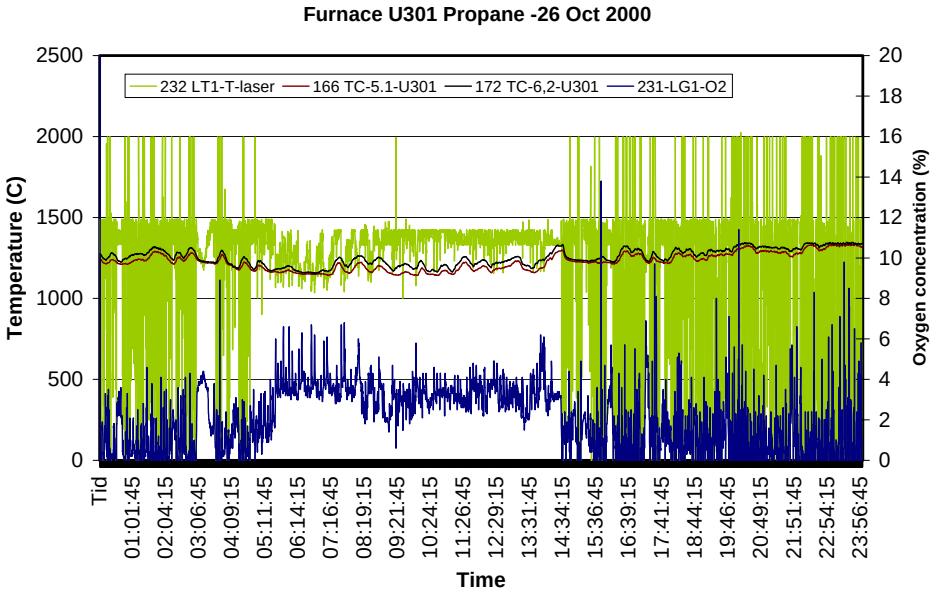

Figure 8. A period of stable measurements in furnace 301 with 4 % O_2.

Enlarging the time scale for the same data in Figure 9 below shows that 1-2 % oxygen could be measured with a gas temperature of 1400 °C. Another interesting observation is the correlation between gas temperature and oxygen concentration. The gas temperature dropped from about 1400 °C at 2 % O_2 to about 1200 °C at 4.5 % O_2. Other factors could also be present to cause this change, but high levels of excess air have a cooling effect and can reduce furnace efficiency and productivity.

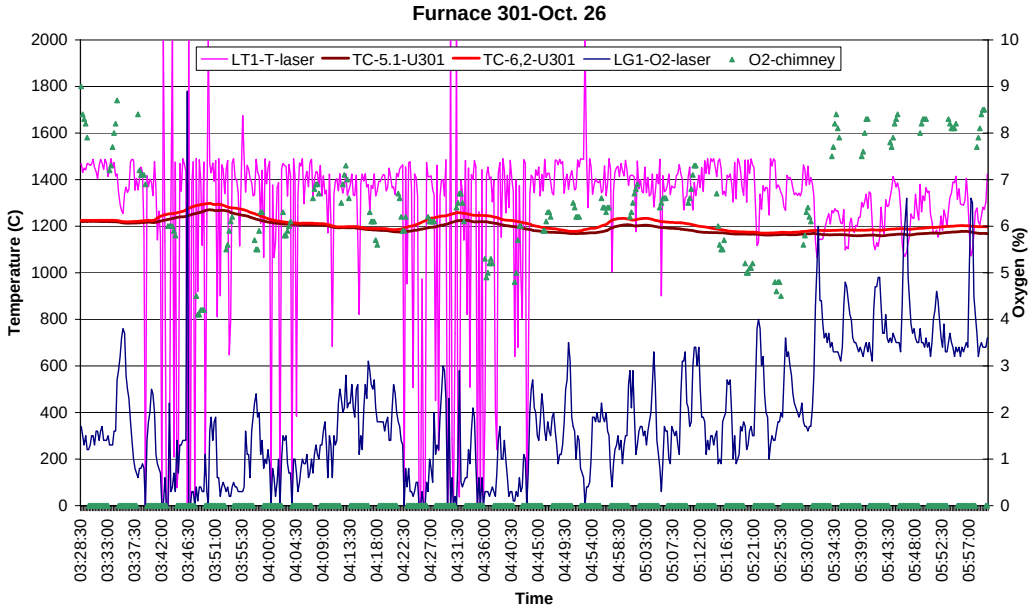

Figure 9. TDLAS temperatures and oxygen concentrations in Furnace 301 October 26, 2000 showing good measurements at 2 % O_2.

A trial with a slab temperature data logger was made December 6th together with another project. The test slab surface temperatures in the soaking zone are plotted together with the furnace gas temperature. There were large oscillations in the gas temperature, slight oscillations in the wall temperature, but the slab temperature increased nicely. Slab temperature prediction appears to work well with steady production despite the large swings in gas temperature, but they increase the risk for inaccuracies in slab temperature prediction during variable production rates. The swings in the gas temperature appear to be partially related to the swings in the fuel flow.

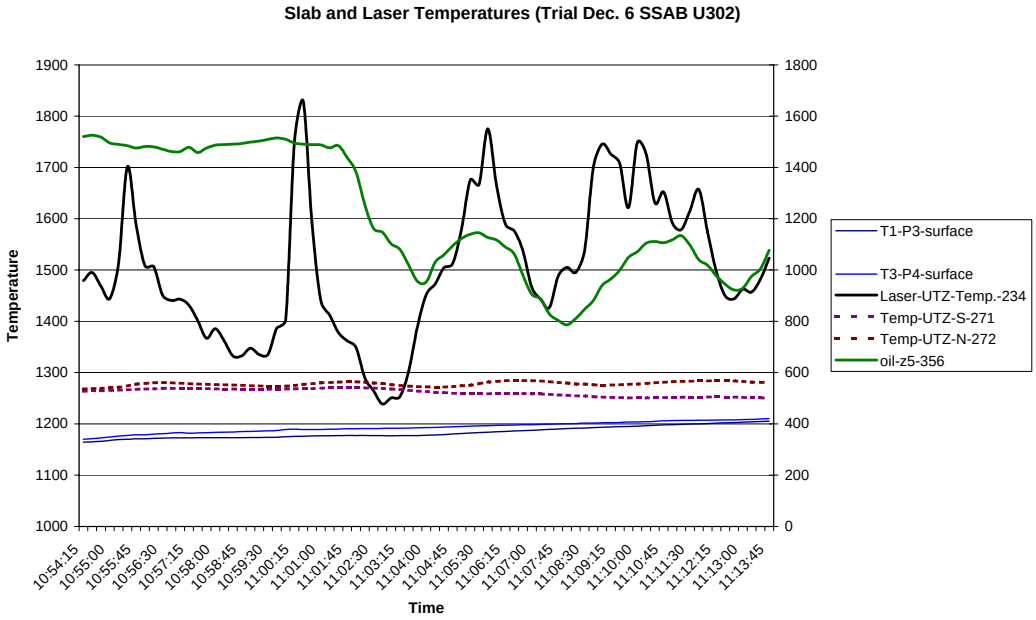

Figure 10. Gas, wall and stock temperatures from a data logger trial.

Examining the same data from December 6th on a plot with the discharge door opening data, shows that the peaks in the TDLAS gas temperature occurred together with drops in the oxygen concentration when the discharge door was opened. This is the reverse of that expected with a burst of cool, oxygen rich air from the discharge door. This is probably at least partially related to the mathematical method used within the instrument to calculate the gas temperature from the shape and position of the absorption peaks. The instrument is designed for uniform gas temperatures, so a burst of colder, oxygen rich air can distort the absorption peaks and give erroneous readings. A high gas temperature reading then distorts the oxygen concentration calculated, since the oxygen concentration is inversely proportional to the gas temperature from the ideal gas law. Note that the TDLAS gas temperature in zone 1 dropped slightly, as expected when the door let in cooler air. An additional factor is the swings in burner output as shown by the swings in the oil flow rate to zone 5, which are expected to give true swings in the gas temperature (see Figures 11 and 12).

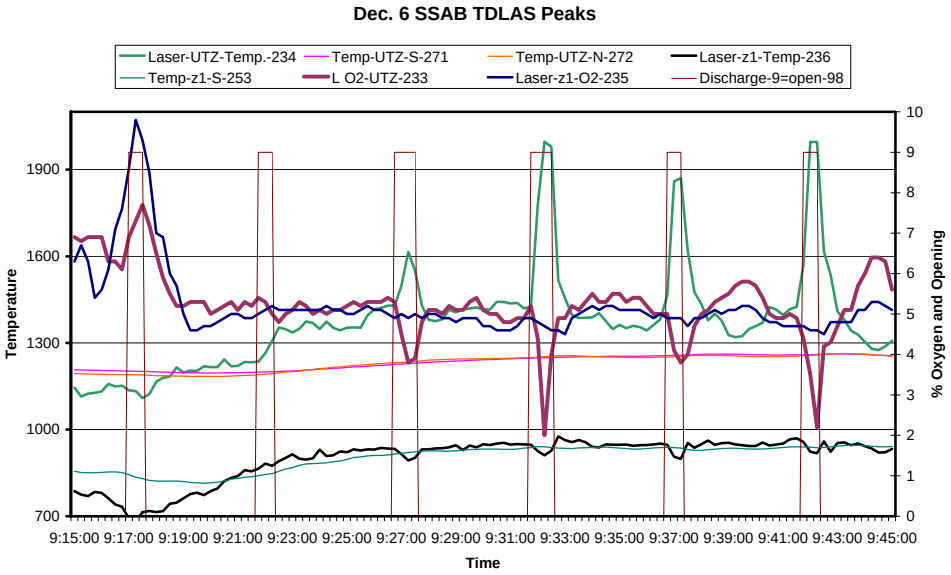

Figure 11. Temperature peaks associated with discharge door opening on Dec 6th.

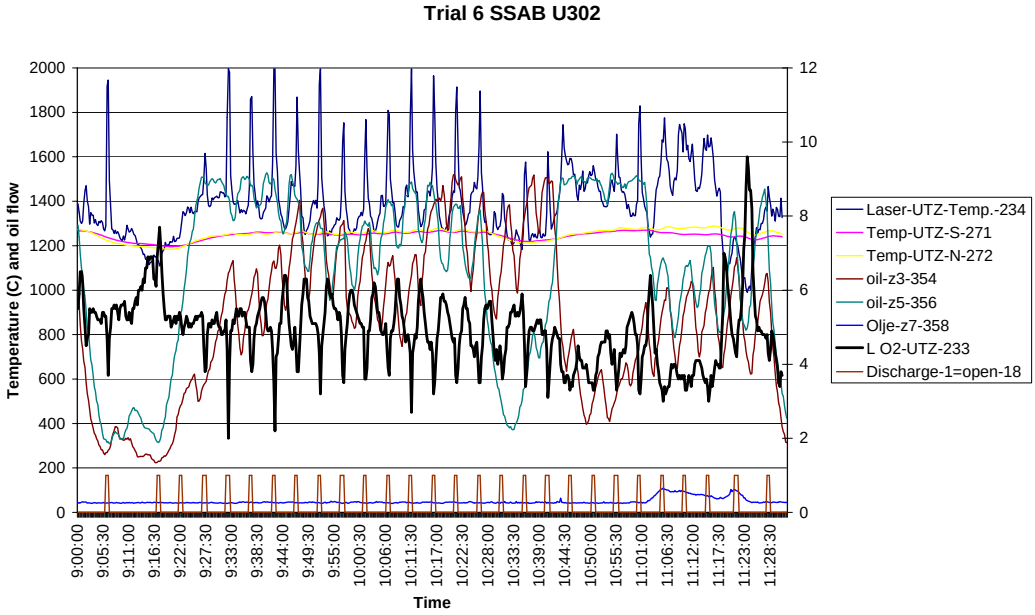

Figure 12. Swings in the oil flow rate triggered when the discharge door was opened during the Dec 6th trial.

The zirconia probe was not working during the December 6th trial, but an extractive measurement of the oxygen concentration was made with a Quintox electrochemical oxygen analyser. Gas was extracted with a metal tube riding on a steel ski above the slabs together with a type K thermocouple to record an approximate gas temperature near the laser beam. The steel ski acted as a radiation shield from the cold slabs, so the thermocouple temperatures recorded was surprisingly close to the temperature from the TDLAS. The small oscillations are due to the on/off cycling of the regenerative burners in zone 1. The extractive oxygen concentrations corrected to wet concentration also followed the TDLAS data. This steel ski technique appears

to be a simple method to check the calibration of the TDLAS measurements in zone 1.

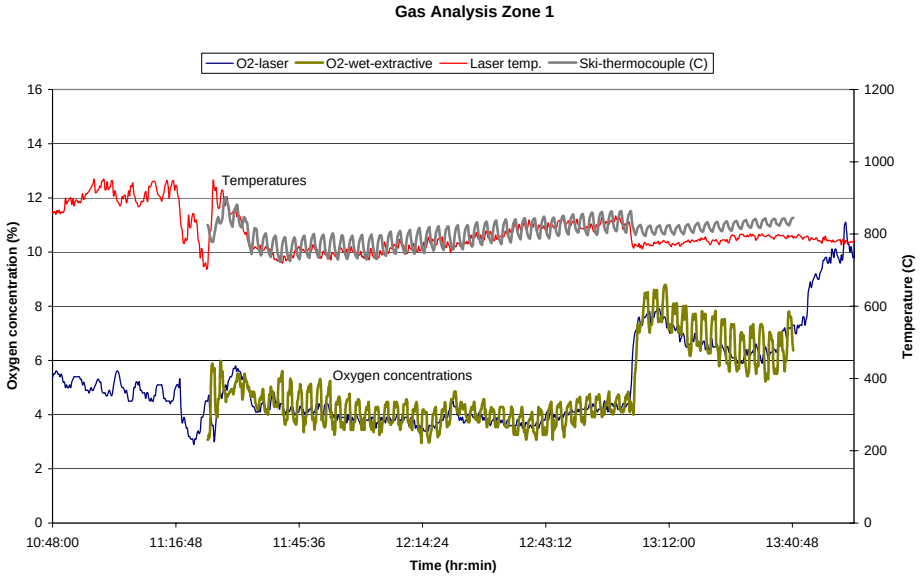

Figure 13. Extractive gas analysis in zone 1 with the steel ski technique.

The gas temperature measurements were sometimes rather high (about 1600 °C) and sometimes rather low (about 1000 °C). For example, in the figure below the discharge door opening shows production at 18:05 with a gas temperature of about 1000 °C. These large swings in the gas temperature during steady production are undesirable for maintaining uniform slab temperatures. A gas temperature of 1000 °C would reflect a rather low slab temperature, since the slabs are the cold heat sink in the soaking zone. These results would indicate the importance of continued research into measuring furnace gas temperatures, and some tests have been made with a CO_2 radiation pyrometer in another project JK5151.

It can be concluded that combined gas temperature and oxygen concentration measurements with the TDLAS are unsuitable for the soaking zone. Separate gas temperature measurements appear to be a requirement for obtaining accurate and stable oxygen measurements in this zone, which are a requirement for using the signal for automatic excess oxygen control. These trials with TDLAS were the first known application to this large of an industrial reheating furnace. The results were promising for this new technology, and worth future research, even though these trials were not completely successful. The international interest in this research with TDLAS is reflected in the number of MEFOS conference presentations and articles about this topic [8-11].

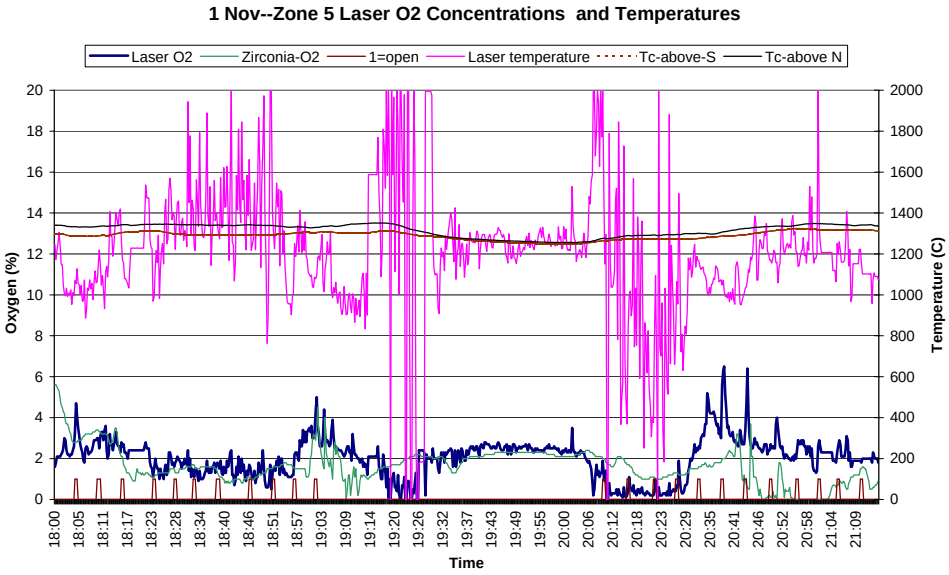

Figure 14. Periods with low gas temperatures in zone 5, and irregular agreement between the point and average oxygen concentration measurements.

2.1.2 Trials June 2001 with NEOs Laser Gas O2 Monitor

The trials at SSAB with NEOs TDLAS instrument were about a half-year after the first trials with the Siemens instrument. NEOs instrument is mounted near the furnace instead of in a control room, since no fibre optic cables are used. Therefore, the analysis electronics are in an enclosure where the furnace heat is a potential problem. The instrument was mounted in zone 1 where the ambient temperature is normally lower and safer for the instrument, and the gas temperatures are lower making it less difficult for measurements. An example of the stability of the measurements is shown below. The zirconia probe used for comparison, and the two measurements were in general agreement.

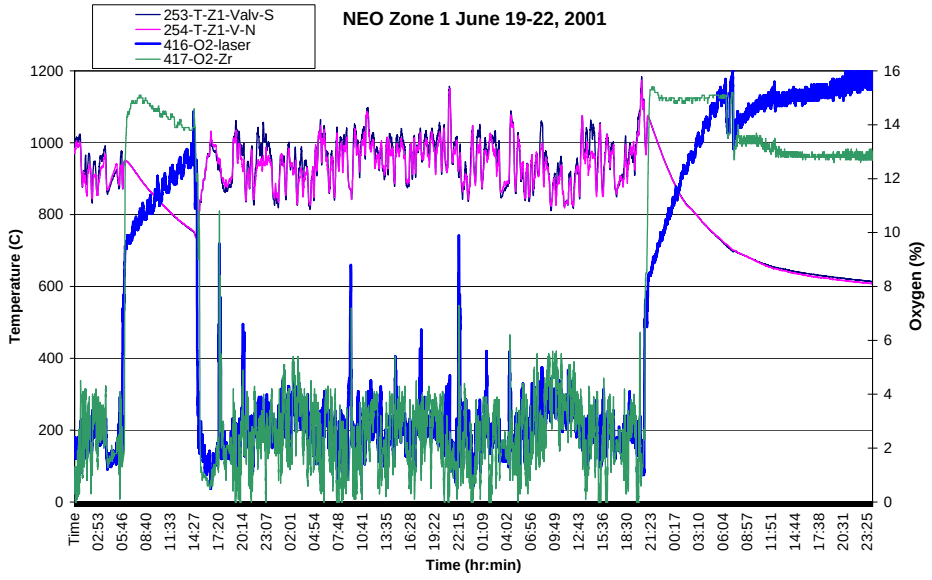

Figure 15. Stable operation of the Laser Gas Monitor in zone 1.

An enlarged time scale is required to compare the zirconia probe measurements with the TDLAS measurements better. The figure below shows the quick response of the in-situ laser measurements at about 5:50. Automatic control is simplified with a fast and accurate response to system changes. The laser signal was also more stable with steady operation at about 2-3 % oxygen while the zirconia signal was more variable about midnight to 2:00. A non-representative local oxygen concentration is unsuitable for controlling all the burners in the zone. Gases from the other furnace zones are expected to have a greater negative effect on point measurements than an average composition.

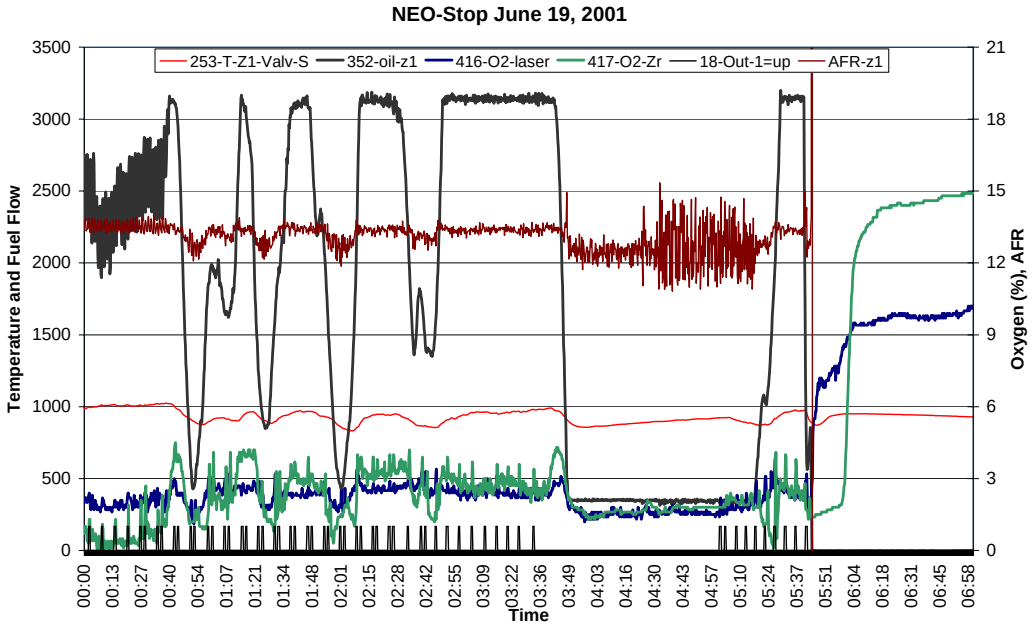

Figure 16. Oxygen measurement with the fuel flow rate and AFR showing a slight drop in the AFR about 3:50 affected the measurement average.

A third oxygen concentration can be derived from the fuel and airflow rates or the air-to-fuel ratio (AFR). This calculated concentration can be used together with the other two oxygen measurements to help determine which measurement is better. A plot of the 3 methods shown below, and the laser measurement appears to be best. Sometimes the ZrO_2 probe had large and apparently misleading swings like at 10:15, which potentially could lead to problems if the signal were used directly for automatic excess oxygen control. Likewise, the calculated oxygen concentration could be unusually low relative to either of the measured values, like at 11:30, which could be related to air infiltration.

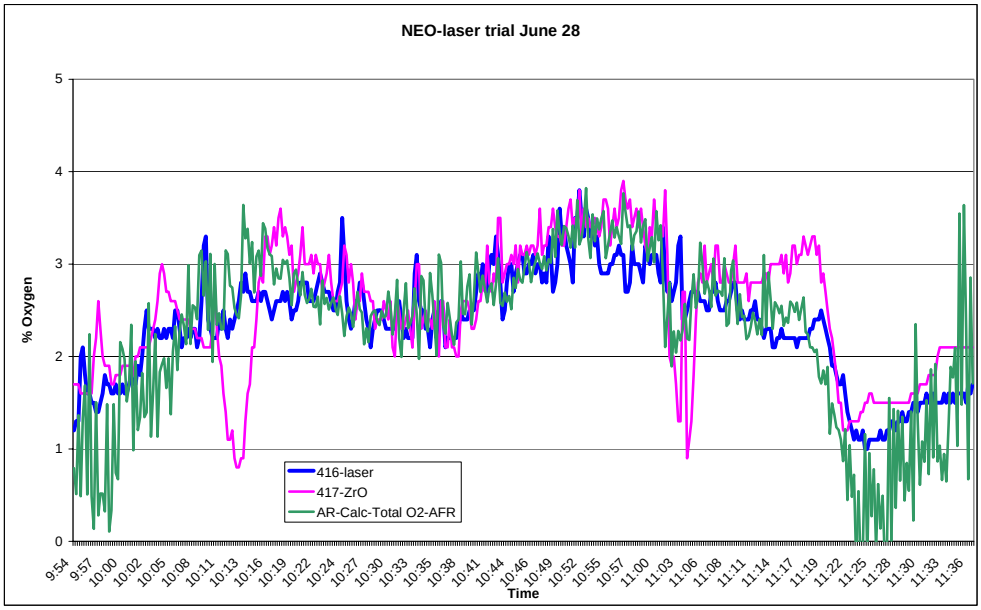

Figure 17. Measured oxygen data with oxygen data calculated from the AFR, which is currently the basis for oxygen control in the FOCS system.

A fourth type of oxygen measurement was made using a steel ski or sled with a metal tube to extract gases for oxygen concentration measurements. The extractive measurements were typically higher than the other 3 methods, so one can suspect an air leakage in the extraction system. The maintenance requirements for extractive systems have made them problematic for on-line measurements, and air leaks are only one of the potential problems (plugged lines, filter changes, condensation removal, etc). The best method for automatic oxygen control appears to be the in-situ TDLAS signal. The zirconia probe gives a signal, which is often acceptable for monitoring the process with moderate oxygen concentrations (2-6 %).

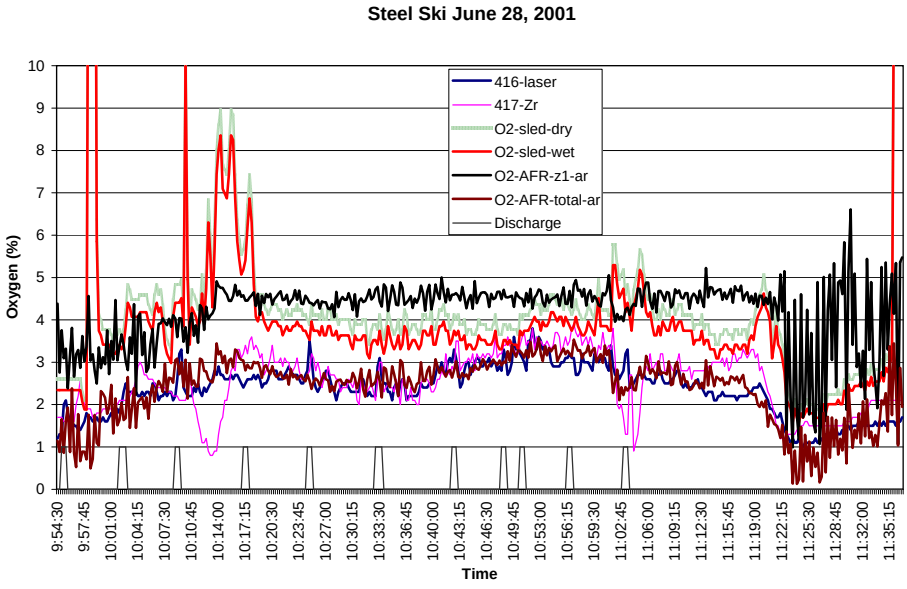

Figure 18. A comparison of four ways to check the oxygen concentration in zone 1.

The oxygen concentration in zone 1 calculated from the air and fuel flows to all 9 burner zones was compared to the measured data from both the TDLAS and the zirconia probe. The correlation was relatively good for the oxygen concentrations present. The zirconia probe had periods with nearly no excess oxygen, which could pose a control problem. Automatic excess oxygen control with TDLAS should be able to control to a lower average concentration. The average oxygen concentration was good for controlling with flow rates at about 2.5 % O_2 for the period June 27-28 (with 2.40 % from the AFR using 10.5 for stoichiometric combustion, 2.68 % with the TDLAS and 2.42 % with the ZrO_2 probe). Most of the data are in the interval 1-4 %, so automatic control should be able to lower the average to perhaps 1.5 % without operational problems, if most of the data were in the lower end of this range (1-2 %). The energy savings of a lower oxygen concentration are discussed later.

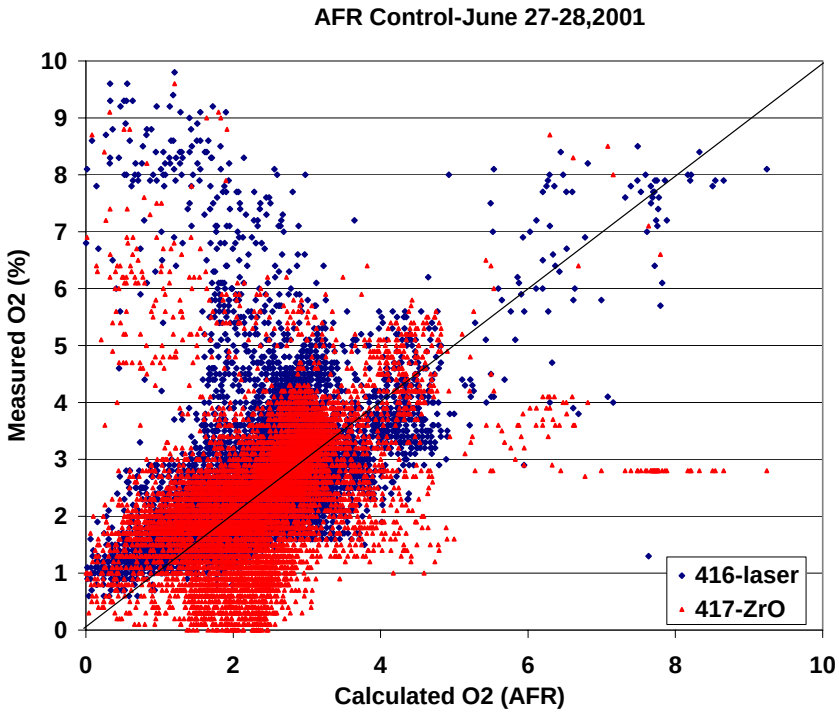

Figure 19. Measured oxygen concentrations versus oxygen concentrations calculated from the AFR.

2.2 Pilot trials

There were questions and problems with implementing TDLAS after the initial industrial trials, so pilot trials were made. One of the questions to resolve were the swings in measured gas temperature, which could affect the oxygen concentration measurements (the oxygen gas concentration is inversely related to the gas temperature in the ideal gas law: Concentration = n/V = P/(RT)). Measurements of the gas temperature in the chamber furnace with MEFOS suction pyrometer were tried, but the water cooling for the suction pipe affects the furnace gas temperature and

burner output, which makes simultaneous measurements with the TDLAS worthless. Another question was the flow rate and cost of the protective purge gas. It would have been interesting to test superheated steam as a purge gas, but the equipment was not designed for operating with the higher gas temperatures. Saturated steam is unsuitable, since it can condense on the lenses. The control system for maintaining superheat in the steam adds to the capital and operating costs of the system. Electrically generated superheated steam could cost about 50 kkr/yr for the Siemens TDLAS, and nitrogen is still required for the electronics boxes. A third item was the instability of the temperature measurements with the Siemens TDLAS in the SSAB trial. This problem could be eliminated by new software from Siemens within the instrument, which eliminated the directly coupling of the gas temperature measurements with the oxygen measurements.

2.2.1 Chamber furnace trials

The NEO TDLAS was installed in MEFOS chamber furnace along the length of the furnace (about a 3 m path length) and a trial was made to investigate its performance. Alignment of the instrument is more difficult than for the Siemens instrument, so a representative from NEO aligned the instrument before the trial. The first test (Figure 20) showed that NEOs instrument responded nicely down to about 0.5 % oxygen on the 3 m path length (1.5 %-m) at a furnace set point temperature of 1050 °C, which would be equivalent to 0.1 % oxygen for the 12 m path length at SSAB. This high of a sensitivity was not observed for the combined gas temperature and oxygen concentration measurements with Siemens TDLAS.

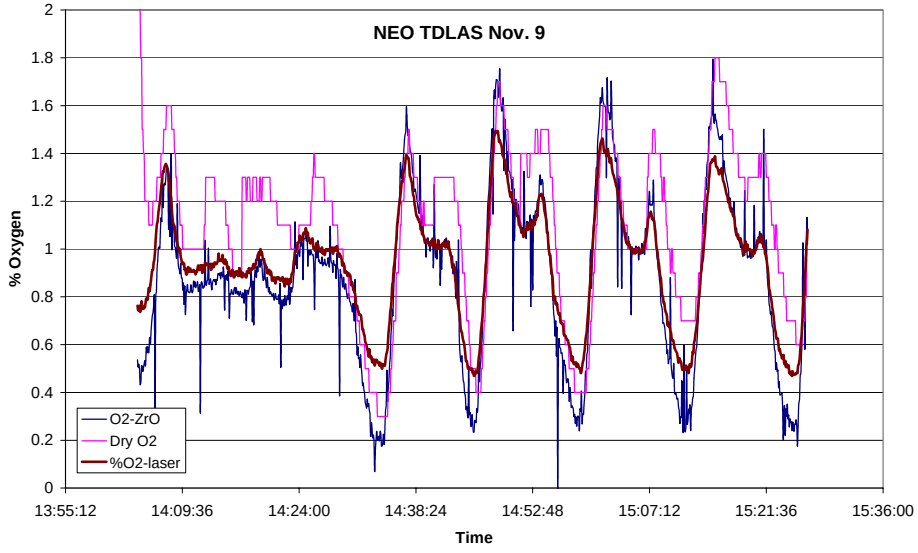

Figure 20. Good accuracy for NEOs TDLAS at a low oxygen concentration.

The instrument is designed to operate with air as a purge gas, with an air compensation factor in the software. The absorption peaks chosen in the instrument are not supposed to be very sensitive to oxygen in cold purge air. Figure 21 shows how the

switch from nitrogen purge to air purge at about 16:03 gives a large jump in the oxygen concentration readout, from about 2 % to off-scale at about 48 % oxygen. Note that air cannot have more than 21 % oxygen, and these higher figures are due to how the instrument correlates the absorption measured to the oxygen concentration in the furnace temperature (1050 °C in this trial). Obviously even cold air is a risky purge gas, but one reason it affects the reading so much is that it warms up when the air is blown into the hot furnace. A lower airflow and the use of the correlation program in the instrument should reduce the error. Air compensation and air at 3 bars gage pressure gave about 4 % furnace oxygen with NEOs TDLAS at 16:23 close to the 4.5 % oxygen recorded by the zirconia sensor. Blowing so much air in the furnace increased the furnace oxygen concentration. Reducing the airflow by decreasing the air pressure to 1.5 bars gave 1.4 % oxygen with the TDLAS versus 3.5 % oxygen with the zirconia sensor. Obviously, air was not suitable as a purge gas for this application. The cost savings are not worth the inaccuracies it contributes to the measurements. The gas flow rate was measured with a rotameter (using a floating ball) ahead of the pressure gage and TDLAS. A flow rate of 600 l/hr N_2 at 1 bar (or 20 Nl/min) performed well. This gives a reasonable operating cost of 5 kkr/yr for N_2 at 0.5 kr/m3n. Air might be suitable as a purge gas if the oxygen concentration being measured is relatively high (10-15 %) depending on the path length, so the oxygen in the air (21 %) does not have such a large influence on the absorption peaks.

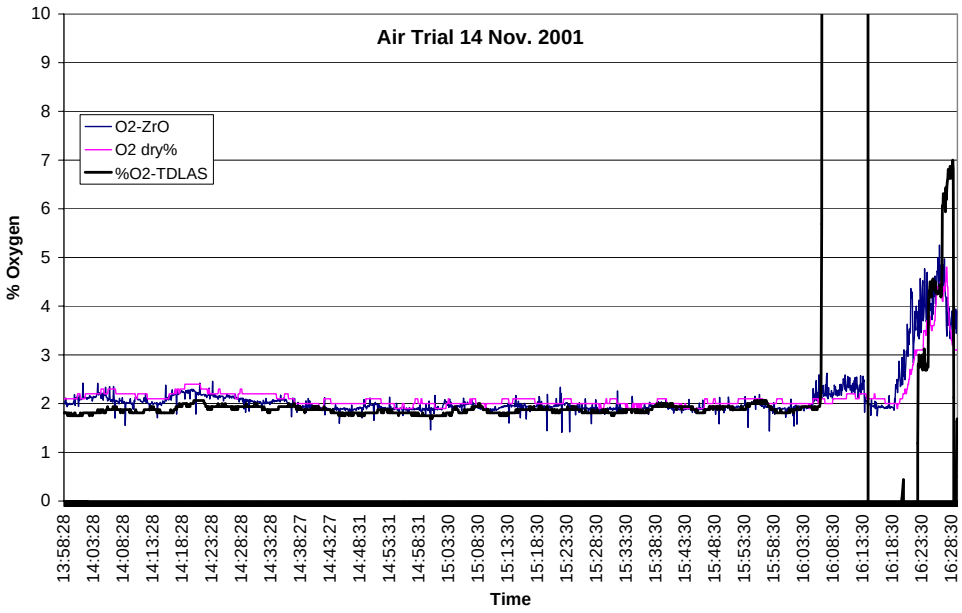

Figure 21. A period of stable operation followed by a test using air purging instead of nitrogen (at about 16:00).

Another pilot trial was made in MEFOS chamber furnace in January 2002 to compare oxygen TDLAS instruments from Siemens and NEO. The instrument from Siemens had been modified so the gas temperature could be entered manually, and the percent excess oxygen could be independently measured. The NEO instrument

was designed only for oxygen measurements, so combined gas temperature and oxygen measurements were never a problem with it. The NEO TDLAS was left measuring the length of the furnace (3.1 m path length), while the Siemens TDLAS had a shorter diagonal path (1.1 m). Figure 22 illustrates how the gas temperature measurements were impossible with low specific oxygen concentrations (% oxygen * meters). The temperature readings went to zero with the lowest oxygen concentration, were abnormally high with modest oxygen concentrations, and finally, the temperatures were realistic with the highest oxygen concentrations (about 10 % oxygen over 1.1 m or 11 % O_2-m). The purge gas to the NEO TDLAS was nitrogen through the trial, which provides a reference. The purge gas system was not apparently connected correctly for the NEO instrument, so a correction of 20 % (factor 0.8) was used on the data to adjust for the path length (therefore the label "NEO-corr"). A detailed view of the stair-step increase in oxygen concentration is shown in Figure 23.

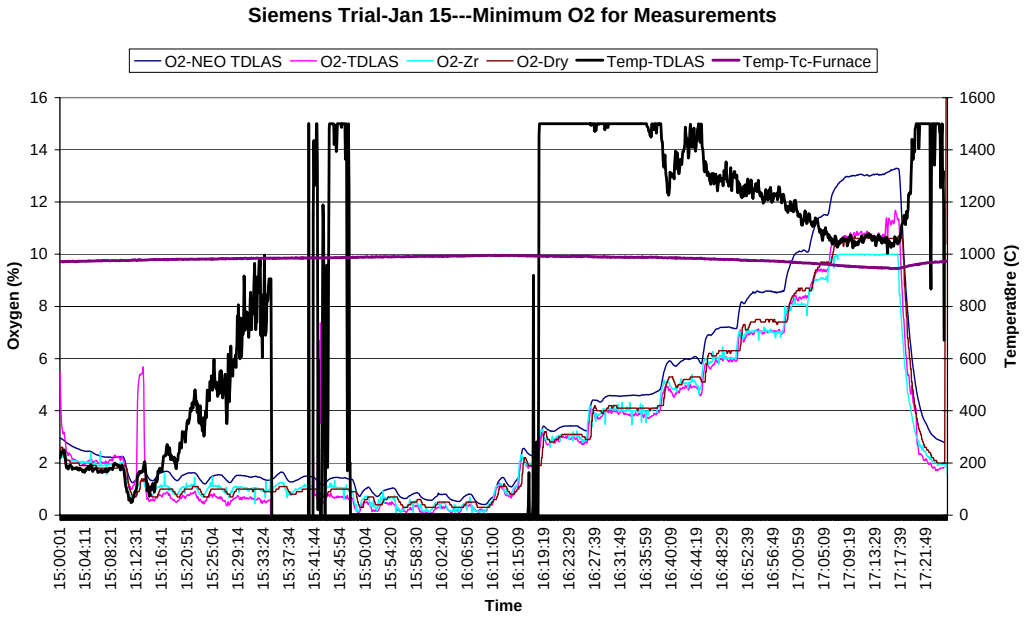

Figure 22. A comparison of the two TDLAS instruments with stable oxygen concentrations, even with swings in the TDLAS gas temperatures.

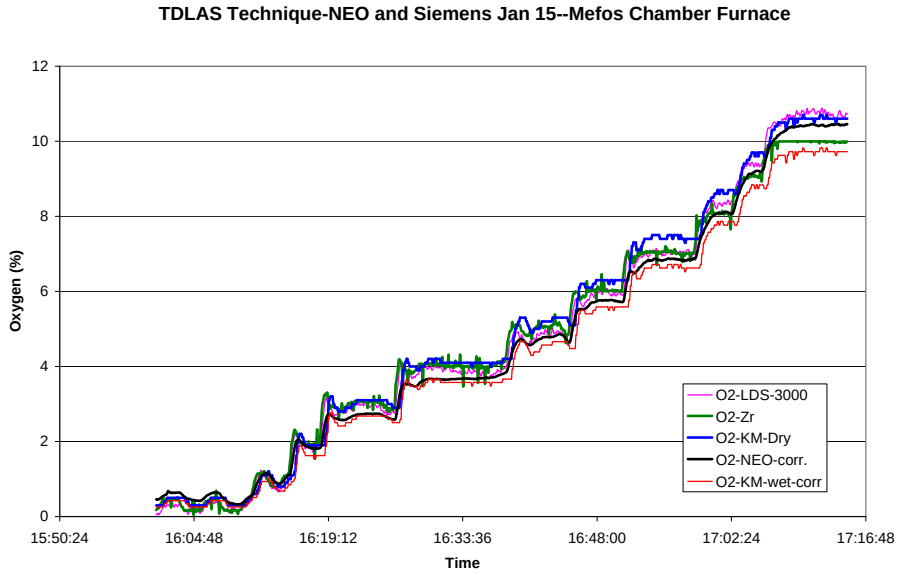

Figure 23. Oxygen concentrations measured with two TDLAS instruments, versus zirconia and electrochemical based point measurements.

The effect of using air for a purge gas was also tested for the Siemens LDS3000. The furnace temperature was set at about 1100 °C with a stable oxygen concentration (3 % on the TDC2000 controller). The laser temperature measurements were at about 1200 °C with nitrogen purge. Opening the sender unit door gave a drop in the temperature readout to about 450 °C, but there was little effect when air entered the receiver unit with an open door. The response when going from air back to nitrogen in the sender unit is shown in the figure below, how the measured temperatures climbed back up. The effect of air was repeated at 13:30 showing how the cold purge air to the electronics boxes quickly affected the temperature readout. At 13:44 air was sent to both the receiver unit and the lens tube. This caused the oxygen readout to increase and the temperature reading to decrease. Varying the air flow rate changed the oxygen reading, initially about 5 % at 0.4 bars, to 4 % at 0.2 bars and up to 8 % with 0.5 bars. Going back to nitrogen for the lens tubes gave a good oxygen readout, but air in the electronics units ruins the temperature readings. The lack of effect of cold air in the electronics boxes on the oxygen readings is positive. A representative from NEO stated that the choice of peaks can be made for a reduced sensitivity to cold air. Nitrogen is not required for only oxygen measurements with Siemens TDLAS, since steam can be used to purge the lens tube and air the electronics boxes.

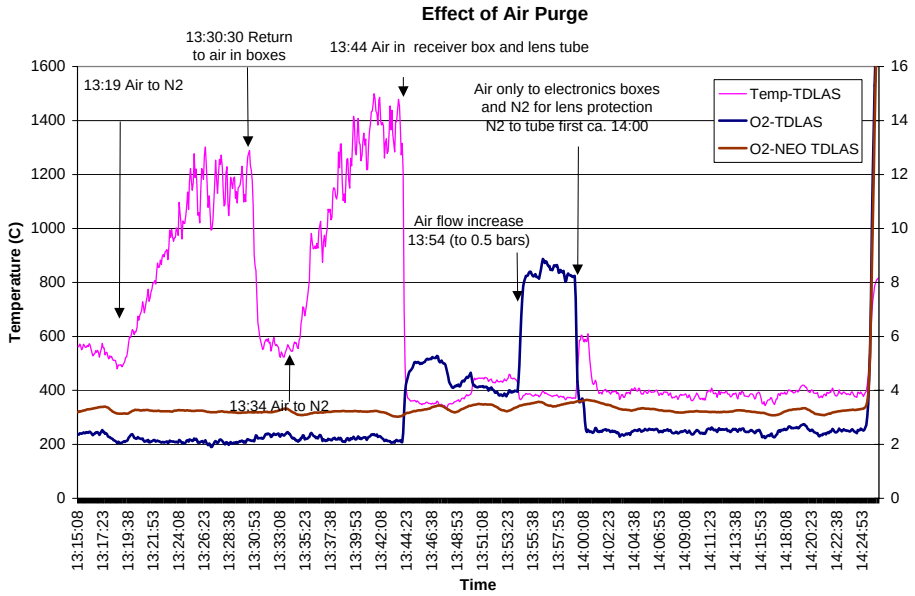

Figure 24. Effect of air purge on the Siemens TDLAS with NEOs TDLAS as a reference.

The TDLAS was found to give a stable signal in the chamber furnace, so a trial was made with automatic oxygen control in MEFOS WBF. The manual temperature mode was chosen for calculating the oxygen concentrations, to avoid problems with swings in temperature from the LDS3000. A period using automatic controls from the TDLAS signal is shown in Figure 25 below. The zone 2 temperature and oxygen concentrations were varied as shown by the thermocouple and ZrO_2 signals. The furnace was empty firing light oil, so the burner output could be quite low with steady operating conditions. The temperature was increased from 1150 to 1200 °C at 11:02, then the oxygen concentration was decreased from 1 % to 0.5 % at 11:15. Note that the zirconia signal is typically less than the average from the TDLAS. A test with the TDLAS using 0.3 % oxygen in the furnace, beginning at 11:48 lead apparently to burner smoking and a loss of the signal. Oil burners have difficulty operating without smoking with low oxygen concentrations, so 0.5 % oxygen can be considered a reasonable lower limit (0.5 % on 2.2 m is 1 %-m). This is sufficiently low for industry, since it corresponds to 0.1 % on 12 m. Signal conditioning is required for automatic oxygen control with lower oxygen concentration, to avoid control problems with artificially high oxygen concentrations with a loss of beam transmission. The instrument readout did not drop to zero oxygen, so transmission or a negative temperature readout are better indicators for the loss of the signal.

A stair-step increase in the oxygen concentration was made with about 5 min intervals, 0.75 % to 2 % at 13:16, to 4 % at 13:21, 6 % at 13:26 and 8 % at 13:31. The TDLAS gas temperature (800 °C) became more realistic at the high oxygen concentrations, but still far from the expected value. The difference in the measurements between the zirconia and TDLAS can partially be explained by an unknown gas temperature. The gas temperature was manually fixed to the TDLAS, while the increase in excess oxygen increased the burner output. The furnace temperature was

decreased to 1150 °C at 13:49 and the oxygen set point shortly after at about 13:54 from 8 % to 4 %, and 1 % at 14:12 and 0.5 % at 14:24. The system was unstable at these low oxygen concentration and the signal was soon lost with negative temperatures.

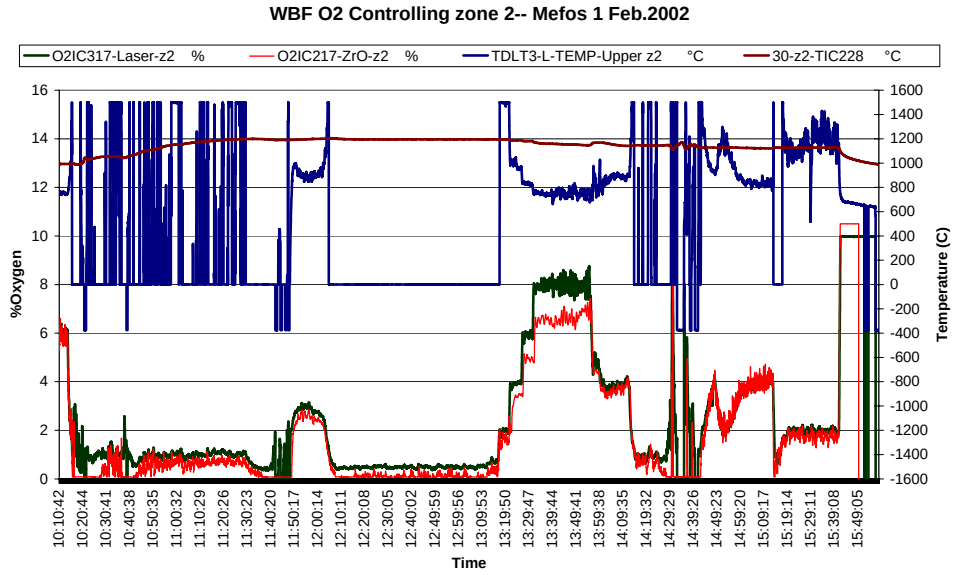

Figure 25. Automatic excess oxygen control in MEFOS WBF.

In summary, pilot trial were made to see how low of an oxygen concentration is possible. The lower limit for either the Siemens LDS3000 or NEO Laser O2 Monitor was not reached with the minimum practical operating limits of our furnaces (a 0.3 % furnace set point oxygen for 1.1 m or about 0.3 %-m for the LDS3000 in the chamber furnace). One can divide 0.3 % by 12 for the effect of path length at SSAB, which means from MEFOS test that the TDLAS technique should work at least down to 0.03 % oxygen at 1000 °C at SSAB. There is a temperature sensitivity for oxygen measurements, but there is a potential for detection of even lower oxygen concentrations according to the manufacturers data. The LDS3000 detection limit is 200 ppm (0.02 %) oxygen for 1 m (equivalent to .0017 % for 12 meters), but the measurement temperature is not stated. A detection limit of 0.01 % is given for the NEO TDLAS instrument.

The problem with gas temperature measurements requires investigation by Siemens. It could be related to the calibration technique (100 % oxygen and 645-900 °C instead of low oxygen concentrations and high temperatures (for steel reheating, 5 % oxygen and 900-1100 °C would be preferable). When the gas temperature is inputted externally, then the oxygen concentration can be measured with a high sensitivity. A high accuracy in the oxygen measurements requires a high accuracy in the gas temperature measurements. The use of a simple thermocouple to give the furnace temperature can lead to errors, and probably contributed to the difference between the zirconia and TDLAS measurements sometimes seen in Figure 25. Gas

temperatures can be measured by other techniques, for example, with a CO_2 radiation pyrometer [12].

3 EXCESS OXYGEN CONTROL - THEORY AND PRACTICE

Problems in reliably controlling the combustion gas composition in steel reheating furnaces include the control strategy required for automatic control, the difficulty in measuring a representative oxygen content in each control zone, as well as the expense and maintenance required for the measurement equipment. Two promising alternatives are (1) conventional zirconia sensors or (2) new TDLAS oxygen analysers. Automatic excess oxygen control has already been tested in reheating furnaces using zirconia type sensors, for example, in MEFOS pilot 3 t/hr WBF and in an industrial furnace by BFI. MEFOS has had automatic excess oxygen control in the pilot furnaces for decades, but it has been difficult to transfer this technology using zirconia sensors to industrial furnaces [13]. BFI demonstrated automatic excess oxygen control using zirconia technology in a natural gas fired reheating furnace after comparison with extractive gas analysis using mass-spectroscopy in two industrial furnaces, one at NMH (Neue Maxhutte, Germany) and the other at Sidmar N.V. (Belgium) in an ECSC project [14]. The oxygen control concepts studied by BFI will be discussed later. Sulphur dioxide and carbon monoxide can be detrimental to zirconia probe electrodes, although there are electrodes that are designed to resist degradation in these harsh gas environments [15]. Natural gas is a low sulphur fuel which burns quickly, which make gas furnaces an easier application than oil-fired furnaces for zirconia based technology.

A review will be made first to examine the physical behaviour of gas flow in furnaces then for practical experience related to controlling the furnace atmosphere.

3.1 Control of gas flow and composition in furnaces

Some factors to consider when analysing the gas flow in furnaces are (1) the response time, (2) the control range and (3) interactions possible for the system for the process conditions and equipment chosen. First, the response time is highly dependent on the burner flow rates and the furnace size. A simple model was made for zone 1 of furnace 302 at SSAB with high burner outputs (in Mathcad, see Appendix 1). The model assumes a low percentage excess oxygen from the middle of the furnace (1 % O_2) which is desirable for minimising scale losses. Zone 1 has a large burner capacity, so a relatively fast response was possible (under 1 minute) when going from 2 % O_2 to 2.8 % O_2 when operating at a high furnace capacity. Note that this change required increasing the oxygen in the combustion products from the burners in zone 1 to 6 % O_2 to compensate for the large volume of combustion gases at 1 % oxygen from the previous furnace zones, (see Figure 26). Reducing the flow of combustion gases to 1/5 increased the response time by a factor of 5 with the same limiting oxygen concentration.

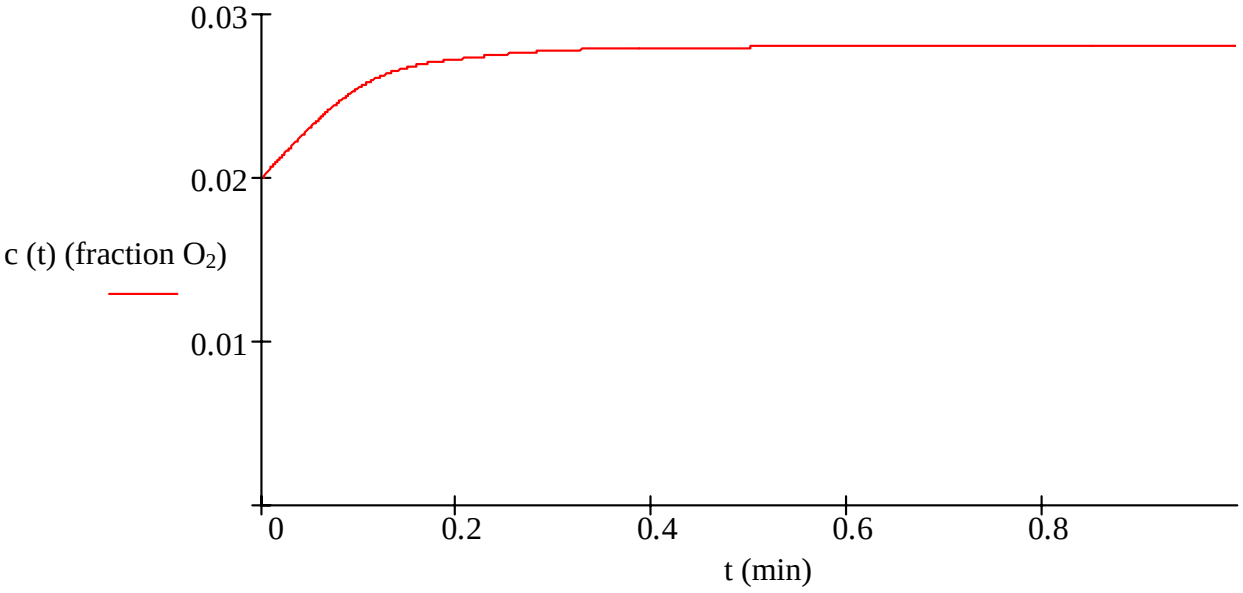

Figure 26. The response curve for time in minutes for the oxygen concentration (c (t)) leaving zone 1 based on a well mixed model at about 300 t/hr (see Appendix 1).

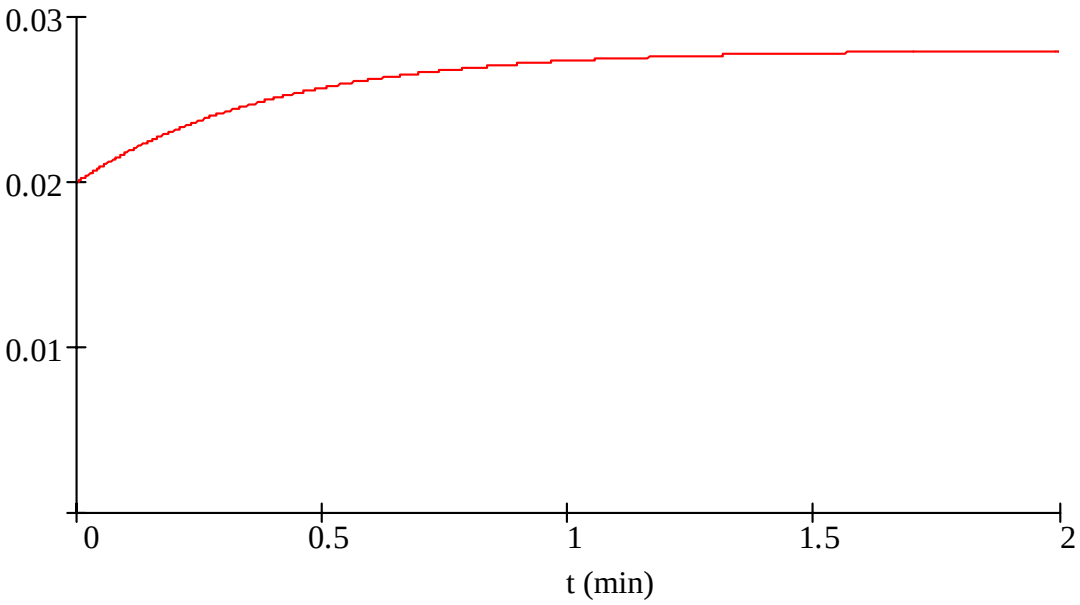

Figure 27. Response to the same step change in oxygen concentration after reducing the burner flow rates to both zone 1 and the other zones to 1/5 or 20 % of their former values.

Slow changes are usually desired in large reheating furnaces, so the fast response time is not an important issue for small changes with a high burner output. The response time is basically fixed for a given furnace and burner flow rates, so the response time is important to remember when tuning the control system.

The second factor to consider for control is the limits for the range of operation, for example, the air supply can be insufficient to maintain the oxygen set point concentration. A alarm or top level controller can monitor the system to make sure that the readings are reasonable and that all the zones are operating within their flow range so no flow is completely shut or fully open.

The final factor is interactions. MEFOS has a cross-regulation controller for which both the temperature and oxygen signals are used to regulate the fuel and air flow rates (Figure 27). When the burner output should be reduced, then the fuel flow should be reduced before the air flow. A load increase gives the reverse response, the air is increased before the oil, so there is always sufficient air for good combustion.

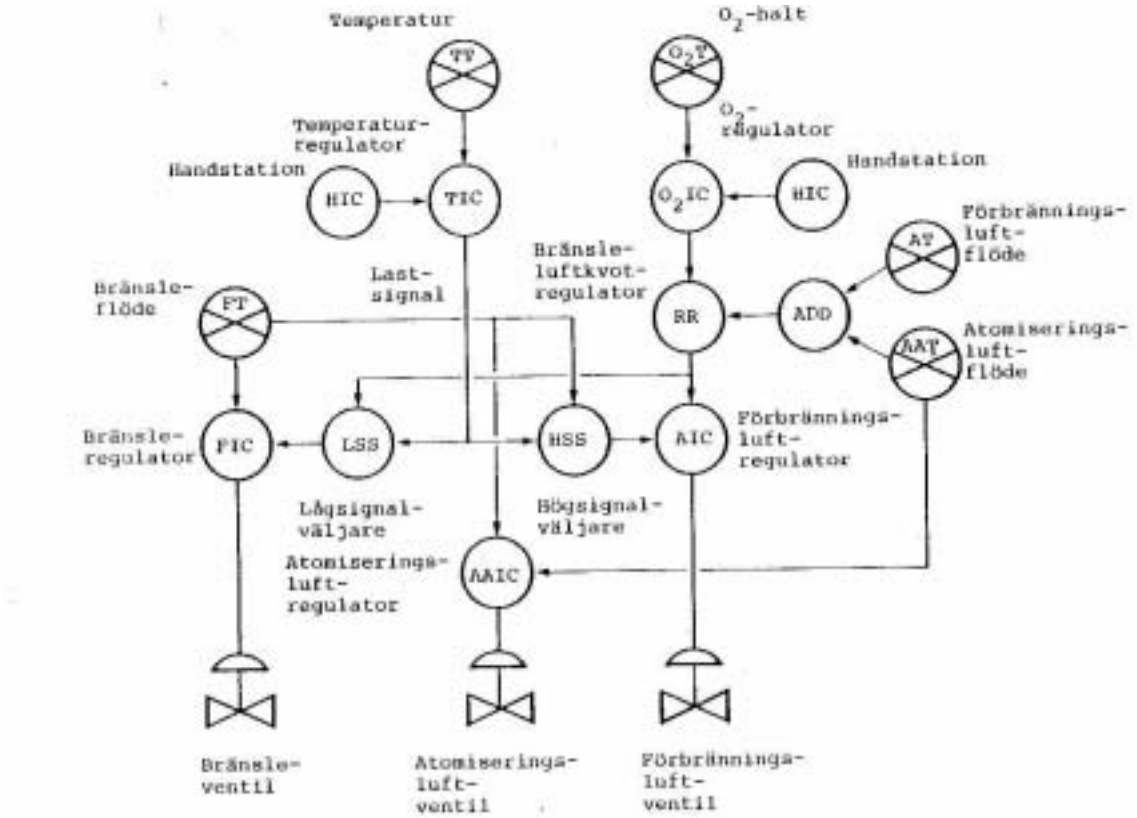

Figure 28. A schematic of the burner control system for automatic excess oxygen control at MEFOS [13].

3.2 Application of automatic excess oxygen control

Both MEFOS and BFI have tested automatic excess oxygen control or air-to-fuel ratio (AFR) control using zirconia sensors in reheating furnaces. Advantages of the zirconia type oxygen analysers include a modest price, low maintenance costs, fast response, simple installation and good sensitivity. Disadvantages include potential damage in the presence of certain gases as CO and SO_2, short useful life at high temperatures (T> 1300 °C for in-situ models), and point measurements. BFI compared three excess oxygen measurement methods, using equipment from mature technologies (no optical methods as TDLAS were tested in their research). The 3 methods were conventional zirconia probes, a mass spectrometer and paramagnet oxygen analysers. They evaluated the capital costs as well as the maintenance costs for the equipment, and came to the conclusion that the most economical solution for the furnace at NMH were the zirconia probes. Zirconia probes have been on the market many years, and they have been used in many test installations for furnace monitoring, including at SSAB. There is a reluctance in industry to trust these zirconia probes for automatic control of the furnace, when they tend to give so many problems. This project has investigated TDLAS, which is potentially more reliable and accurate, and therefore better suited for industrial burner control.

Research has been directed towards developing newer and better zirconia analysers, including research at BFI recently on a new measuring device called the “integrated measuring probe” [16]. This probe measures both the furnace chamber temperature, as well as the oxygen concentration close to the stock. The integrated measuring probe gives the opportunity to monitor the stock reheating in a new way compared to conventional measuring techniques, as it monitors the environment near the stock. Combustion gas analysis with the integrated measuring probe gave good results. The analysis is based on a ZrO_2-cell outside of the furnace, but directly connected to the integrated measuring probe. The combustion gas is supplied to the ZrO_2-probe by natural convection. In this way expensive and maintenance intensive extractive analysis equipment is not necessary, that is, heated sampling tubes and extraction pumps. The installation costs are reported to be lower than for a conventional system together with low maintenance costs.

The air/gas ratio in each furnace zone was controlled in the normal way by BFI, that is, by using a double cross controller (see Figure 28 of interlinked burner control at MEFOS). The furnace at NMH had zirconia probes in low temperature positions (chimney and preheating zone ceiling), so BFI added 5 additional probes to burner zones 2-6, so that automatic excess oxygen control was possible in 6 of the 7 burner zones of the furnace. The probes should be generally located near the middle of the zone away from flames, with at least one probe in each burner zone. Experimental tests can be used to find a good position, but BFI found that the location of the probes was not as critical as they first assumed [17].

The incoming oxygen measurements are treated using a special filtering algorithm, that is, a sliding window minimum filter. Using this filter only the minimum value

of the oxygen concentration obtained during the last time period is used for control purposes, such as, the last 2 minutes. A “minimum filter” was not required for the Sidmar furnace with slow measurement equipment [18]. Experience shows that in this way the control of the oxygen content is better than when using a fast controller trying to smooth all of the fluctuations which might be very high (up to +/- 2 % oxygen, depending on furnace load). The addition of a filter to take only the minimum oxygen level from the incoming oxygen signal was found to be necessary to avoid carbon monoxide in inadmissible amounts.

The supervising rules module consists of several independent rules. One of the rules is a plausibility check of the oxygen measurements. A theoretical oxygen content is calculated based on the volume flow rates measured, assuming that the combustion is complete. A comparison of the oxygen concentration expected from the calculations is made with the measured value, and this comparison shows if the measurement is reliable or not. If the measurement is not reliable a fixed set point for the air/gas –ratio is provided to the controller. Otherwise the measured value is compared to the set point value of the oxygen content. An error of 3 % oxygen was considered acceptable between the calculated and measured values due to the noise in the oxygen signal, air leakage, etc [19]. Based on the error the control algorithm calculates a new set point for the air/gas-ratio.

Another one of the rules is based on the measurement of the carbon monoxide inside the chimney. If high levels of carbon monoxide are detected, then the air/gas-ratio has to be increased. A concentration over 0.01 % CO (100 ppm) was determined to be a high enough CO concentration in the exhaust gases to require adjusting the AFR and the first step was to increase the AFR in the first firing zone by 0.2 [20]. The third module of the feedback controller is the control algorithm itself. This algorithm is based on a simple PI-controller. The necessary controller parameters are adjusted during the initial operation of the controller. The structure of the feedback controller for the oxygen content is shown in Figure 29.

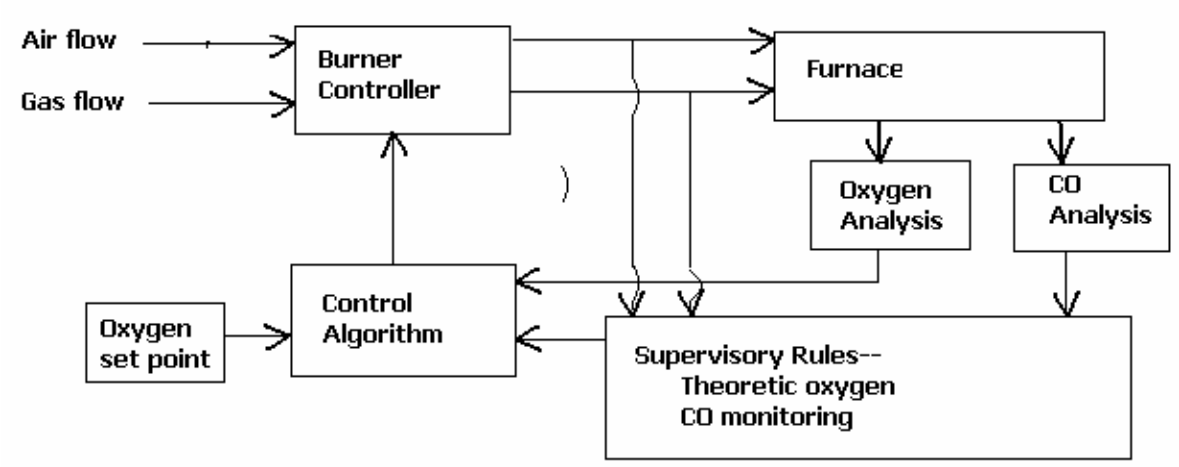

Figure 29. A schematic ~~of the~~ control structure for automatic excess oxygen control by BFI.

An integrated furnace control system based on the feedback control of the stock temperature and the feedback control of the oxygen content is used together with this new equipment. The feedback control of the oxygen content was implemented on two different furnaces and the oxygen content was decreased with 0.5 % up to 1.5 %. An expert system was also developed that gives the opportunity to easily integrate the knowledge of the operational staff to the furnace control system [21].

4 INDUSTRIAL APPLICATION AND ENERGY SAVINGS POTENTIAL

Potential energy savings can be estimated for reduced scale losses and reduced fuel consumption with TDLAS for better process control. First the benefits of reducing the primary or furnace scale losses with automatic oxygen control will be estimated. A survey was made some time ago of scale losses [22] in which SSAB, Borlänge specified a 1 % scale loss in the oil fired Italimpianti furnace (3 % O_2) and 0.5 % in the gas fired Chugai-Ro furnace (1.5 % O_2). Trials were made in the JK project 3258/94 for TO32-40 on various steel alloys and the scaling rate was sensitive to the oxygen concentration for all alloys tested (Ovako 803 ball bearing steel, RR FE430 mild carbon steel, ASM 316 stainless, etc). A coefficient of 0.2 was given for estimating the reduction of scale losses with lower oxygen concentrations [23]. A decrease in the scale losses from 0.5 % to 0.45 % (0.45/0.5 = 0.9 or 90 % of today's scale loss) would give a savings of 0.05 % in yield. This is predicted to be possible if the oxygen concentration would decrease from 1.5 % O_2 to 0.9 % O_2 using the equation:

$$(0.9\%O_2/1.5\%O_2)^{0.2} = 0.9 \quad (1)$$

This is a relatively conservative estimate in the scale loss savings, but the oxygen concentration should not be decreased so much that problems develop with adhesive scale. Assuming an energy requirement of 6 400 kWh/ton from ore to the finished steel product for 5 Mtons steel/yr in Sweden would give a savings of:

5 Mton/yr x 6 400 kW-hr/ton x 0.05 % savings = 16 GW-hr/yr (2)

Next is the energy savings. The oil consumption for Borlänge in the same report was given as 455 kW-hr/ton oil and 380 kW-hr/ton propane in the two furnaces. The energy losses depend on the waste gas temperature and the amount of excess air in the waste gases. Better furnace atmosphere control at the beginning of the furnace could give a larger reduction in the percent excess oxygen there than in the high temperature zones where scaling occurs. An excess oxygen level of 3-6 % from the recuperator is not unexpected with waste gas temperatures from the recuperator of 400-600 °C. A table for waste gas energy losses is given in the ETSU report No 77 Continuous steel reheating furnaces: Operation and maintenance [24]. A waste gas temperature of 600 °C would carry with it 35.4 % of the gross heat in fuel oil (43 MJ/kg) at 5 % dry O2 (4.6 % wet O_2) and if this could be reduced to

3.0 % dry O_2 (2.7 % wet O_2) the loss would be only 32.6 % (a gain of 35.4-32.6 = 2.8 %). Applying this potential energy saving to the entire Swedish production of about 5 Mton/yr of steel would give:

5 Mton/yr x 400 kW-hr/ton x 2.8 % savings = 56 GW-hr/yr (3)

Actual data from the NEO trial for the conditions at SSAB gave an average oxygen concentration of about 2.7 % with the TDLAS in zone 1, June 27-28 as described earlier. The ETSU report states that reducing this by 0.9 % to 1.8 % with an exhaust gas temperature from the recuperator of 500 °C would give a savings of 1 % in fuel (27.9-26.9=1 % less waste gas energy loss). A 1 % reduction in energy consumption on 1 Mtons of steel at 30 l oil/ton and 4 kr/l oil is worth 1.2 Mkr/yr.

BFI has made estimates of the savings for automatic excess oxygen control, and state “The energy savings were evaluated in a range of up to 2.4 %. Nevertheless for less efficient furnaces energy savings might reach values up to 6 %” [25]. Plus savings in reduced steel loss to scale. The zirconia based sensors were chosen for their technical and economic advantages over mass spectroscopy and paramagnetic oxygen sensors. The TDLAS technique was not tested by BFI in their report, but the energy and scale reductions are independent of the measurement technique.

The maximum benefits would be for measurements in every furnace zone, or 8 zones at SSAB. With the present price quotes, the minimum costs would be for the NEO instrument at about 110 kkr/instrument plus electrical, flanges and gas lines, or equipment for ca 1 Mkr for 8 zones. The NEO instrument also requires less nitrogen, which at 10 l/min per box gives a total nitrogen cost of about 40 kkr/yr for 16 boxes with a price of 0.5 kr/ m^3n for on-site nitrogen generation. Mills without nitrogen would have about a 30-50 % higher investment cost for purchase of a nitrogen generator (ca 280 kkr for 22 m^3n/hr for 8 measurement points). Purchase of nitrogen in tubes is uneconomical. (Neither instrument tested is designed for using steam without modifications. The steam needs to be superheated to avoid condensation, increasing system complexity further). Just the energy savings should give a payback of less than a year for the equipment costs for the NEO TDLAS, plus the benefits of better process control, including a more uniform product quality, better NOx control, less scale losses, etc. The Siemens instrument could be preferable for some installations that have high temperatures and vibration at the measurement point, since the laser is located remotely, and optical fibres carry the laser signal to the box.

5 CONCLUSIONS

1. Both TDLAS instruments worked well in pilot trials for measuring oxygen concentrations down to the levels desired for good control (for example, an average excess oxygen of 0.3 % over several meters). The most recent laser diode in the Siemens instrument is said to be several times weaker than the previous laser. Initial tests with the weaker new diode show poorer performance, and it did not work ac-

ceptably in the soaking zone of the 12 m wide furnace at SSAB, but it might be acceptable in zone 1.

2. Temperature measurements with the TDLAS still require high oxygen concentrations and moderate temperatures (preheating zone), which means simultaneous measurements are inapplicable for the soaking zone of reheating furnaces. Under these conditions, a separate gas temperature measurement is required, for example, with the use of an IR gas pyrometer. Gas pyrometers (as the LAND CD1) and other temperature measurement techniques was the topic of investigations in JK5151. Extra instrumentation requirements are a disadvantage that adds to the cost, and complexity of the system.

3. The savings calculated for installation of TDLAS oxygen analysis in reheating furnaces for automatic air ratio control are good, but the technology is still in the developmental stages.

4. Air purging influences the oxygen measurements. Neither instrument has worked well with air purging at the low oxygen concentrations of interest for reheating furnaces. Nitrogen purging adds to the operational costs, and nitrogen can be very expensive if it is not produced at the mill site.

5. Future work should include investigating the effect of furnace gas temperature variations on oxygen measurements and the use of NEOs TDLAS in zone 5 where the gas temperatures are higher. Automatic oxygen control was not tested industrial with a major reason the delay and problems with repairing the Siemens TDLAS.

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CONTROLLING EXCESS OXYGEN

(1) Response time

This is a simple model of zone 1 of furnace 302 at SSAB for which the response time for a step change in the oxygen concentration is plotted using Mathcad.

Where c(t) is the furnace oxygen concentration as a function of time and c(t0) is initially 4 % and the incoming gas has C1 = oxygen concentration, and there is a flow of QZ into the first zone with CZ oxygen.

Enter the desired solution parameters:

c0 := 0.02	The initial zone gas concentration is c0, volume fraction
t0 := 0	Starting time is zero
t1 := 1	Endpoint of solution interval
N := 40	Number of solution values on [t0, t1]
Q1 := 470 Q1	is the flow into zone 1 in m^3n/min
V := 105 V	is the volume of zone 1 in m^3n assuming a temperature of 800C
QZ := 840 QZ	is the flow from the other zones
CZ := 0.01	Where CZ is the oxygen in the gas from the other zones
C1 := 0.06	Where C1 is the concentration of the gas entering zone 1

Now we write the ODE in a more general way so the flow can be easily varied:

Given $\quad c(t0) = c0$

$$c'(t) = \frac{1}{V} \cdot [\, C1 \cdot Q1 + QZ \cdot CZ - [(QZ + Q1) \cdot c(t)]\,]$$

c := Odesolve(t, t1)