JERNKONTORETS FORSKNING

Serie	Nr	Datum	Forskningsuppgift nr
D	**805**	**2003-11-26**	**51051**

(TO 51-39)
(MEF03062)

TEMPERATURE MEASUREMENT TECHNIQUES FOR ROLLING MILL FURNACES

Final report by John Niska, MEFOS

Key words: IR, acoustic, thermocouple, temperature, pyrometer, measurement, TDLAS, iron and steel industry

SUMMARY

Recent advances in sensor technology now provide commercial instrumentation for non-contact average furnace gas temperature measurements, either optically (infrared absorption with TDLAS, or infrared emission with IR pyrometers) or acoustically (acoustic pyrometer). The first two new techniques have been tested in industrial reheating furnace trials. A TDLAS for the simultaneous measurement of the oxygen concentration and gas temperature, sometimes gave good temperature measurements, for example, at SSAB in the first zone (z1) where the temperatures were about 800-1000 °C with a high oxygen concentration (3-5 %). The O2 TDLAS technique for gas temperature measurements failed in the soaking zone (z5) with low oxygen concentrations and high gas temperatures (<1 % oxygen and 1400 °C).

Realistic gas temperature measurements were also obtained with an IR gas pyrometer using CO2 radiation in trials at SSAB and Sandvik. The IR instrument is not limited by low oxygen concentrations, and it has a high accuracy at a modest price. The pyrometer measures the gas temperature in the field of view of the lens, instead of an average gas temperature across the furnace, as for the TDLAS. Gas temperature data can be used to improve the stock temperature predictions in steel reheating process control software like FOCS-RF. Improved stock temperature uniformity can improve product quality and save energy.

Potential energy savings of 9 GWh/year were estimated based for better stock temperature control assuming the technique is implemented for the reheating of 5 Mton/year of steel.

ISSN 0280-249X

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1 INTRODUCTION

This project has investigated furnace temperature measurement techniques in the literature with two review reports [1,2], two industrial trials with an IR gas temperature pyrometer [3] and trial results from related project work with an O_2 TDLAS (Tunable Diode Laser Absorption Spectrometer). The first review report [1] investigated the state-of-the-art in furnace temperature measurement technology, and the second report investigated problems with the use of thermocouples and suction pyrometers [2]. An IR gas temperature pyrometer model CD-1 from Land Instruments International was first tested in a trial in the strip mill furnace at AB Sandvik Steel in Sandviken and then at SSAB Tunnplåt, Borlänge. The TDLAS trials were also made at SSAB Tunnplåt and used a LDS 3000 oxygen analyser from Siemens Laser Analytics.

Both of these instruments tested in this project measure in the IR spectrum. IR radiative techniques are useful for moving objects and extremely high temperatures. Radiative techniques include infrared (IR) detectors (IR pyrometers, IR thermal imaging cameras, etc), spectroscopic techniques (tunable diode laser absorption spectroscopy or TDLAS, microwave absorption, Raman scattering, etc), and heat flux pyrometers. Another non-contact type pyrometer for furnace temperature measurements is the acoustic pyrometer (measuring the speed of sound waves). Some of these techniques will be discussed in their respective sections of this report. A summary of operational limits for various measurement techniques is given in Table 1. Low temperature thermometer principles, like thermal expansion (bimetallic and pressure thermometers) and electrical resistance thermometers (thermisters and conductive sensors) are not suitable for furnace temperature and were not included in this project.

Table 1. Some Operation Specifications for Non-Contact Temperature Measurement Techniques Compared With the Thermocouple (Contact Device).

Method	Max temp	Accuracy	Technique	Advantages
Thermocouples (Type S-ISO 9000* for comparison)	1760°C	±0.2°C+0.01%	Seebeck effect	Inexpensive
IR-pyrometer (KT19*)	2500°C	±0.5°C+0.7%	CO_2 gas radiation	High accuracy for average gas temperatures
Acoustic pyrometer (Agam MMP**)	1927°C	<1.5%	Sound velocity changes	Up to 24 paths for 2D isotherms
TDLAS (LDS 3000***)	1500°C	<5% at 900°C	Absorption spectrometry	Gas analysis is possible

* Data from Pentronics for the Thermo Electric ISO-CAL 9000 thermocouple sensor, and Heitronics KT-19 IR pyrometer.

** Agam MMP from Bonnenberg + Drescher, Germany.

*** LDS 3000 from Siemens Laser Analytics, accuracy from calibration datasheet.

2 IR PYROMETERS

Hot objects and materials emit infrared (IR) radiation, which can be used to measure temperature of the object with proper calibration of the system (for emissivity, etc). There are a wide range of IR pyrometers for various applications. The wavelength used can be chosen to measure emission from a specific type of surface or the gas through which the beam travels. Emission from a surface can be used to measure the temperature of steel slabs, wall temperature or a special known target at the end of a tube. Surface temperatures are traditionally measured more economically with thermocouples, but there are special cases when IR pyrometers are better, for example, if the surface moves, as in the case of steel slab surfaces and for fast 2-dimensional isothermal plots.

2.1 IR Pyrometers for Surface Temperatures

The infrared spectrum lies at wavelengths longer than visible light but shorter than microwaves or radar. Infrared radiation has a wavelength from about 0.7 to 1000 microns (or from about 700 nm to 1 mm, or 14 300 to 10 cm^{-1}). IR pyrometers typically operate with wavelengths from 2 to 20 microns, depending on the material being measured. The emissive power of a black body has a spectral distribution dependent on the temperature of the body based on Planck's law. The peak intensity of a black body at approximately 5780 K is similar to sunlight with a peak intensity in the visible light spectrum (400-700 nm) [4, Siegel]. The peak intensity shifts to the infrared wavelengths for steel reheating furnace temperatures. Even white hot steel with a temperature of 1300 °C has a peak emissivity in the IR spectrum, which makes IR temperature measurements a natural approach for surface temperature measurements.

Avoiding the need to know the emissivity of the target (steel) surface is important for obtaining accurate temperature measurements for varying surface conditions. This is a well-known problem, so there have been various methods to avoid this problem with varying target emissivity. One of the early methods is the two colour or two-wavelength pyrometer, which takes the ratio of the radiation at two different wavelengths. Recently two new methods have been commercialized, (1) multiple wavelength spectrometry (the FAR spectrometer) and laser surface emissivity (Pyrolaser). The FAR Associates FMP2 spectrometer uses a wavelength that begins in the visible region and goes into the near infrared (500 to 1000 nm, note that visible light lies about 400-700 nm). An ECSC study ([5] EUR20463) used a FTIR (Fourier Transform Infrared) spectrometer to detect radiation from 400 to 4000 cm^{-1} (25 to 2.5 microns), which is similar to the technique used in the FAR spectrometer.

The FAR technique in the FMP2 Multi-wavelength pyrometer allows for highly accurate measurements, with a reported accuracy of 0.15 % of the readout (or ± 2 °C at 1330 °C) for grey bodies. The accuracy is less for non-grey bodies at under 0.75 % error, and 0.5 % (± 6 °C at 1200 °C) typically. The FAR instrument reports an accuracy or tolerance of a specific measurement, so additional measurements are possible for increased accuracy. The FAR Associates spectropyrometer technique was marketed commercially in 1997, and currently the base price is much higher than for a conventional pyrometer (24 500 USD in 2000 for a single unit or about USD 35 000for two pyrometers together) [6].

The FTIR spectrometer method used for pyrometry (or spectropyrometer) in the ECSC report mentioned earlier is not available commercially. The instrument is sensitive to parasitic radiation, so a special water cooled shield was made to avoid radiation from the furnace walls. The data presented in the final report is limited [7], but an accuracy of 3 °C for a blackbody at 725 °C indicates an accuracy similar to the FAR method for a grey body. A computer is required to convert the emission spectrum measurements into a surface temperature. The need for a FTIR spectrometer and a computer makes the method expensive, relative to conventional IR pyrometers. There do not appear to be any significant advantages of using the FTIR spectropyrometer relative to the FAR spectropyrometer. An interesting comment in the report related to conventional IR pyrometers is the large variations in the emissivity of samples at low temperatures.

The Pyrolaser from The Pyrometer Instrument Co uses a low-powered laser to measure the surface reflectivity at a specific location and wavelength. All the IR radiation striking the surface is either absorbed (A), reflected (R) or transmitted through the solid (T), so A+R+T = 100 %. Opaque solids like steel have a transmissivity of zero, so the absorptivity is 1-R. The surface emissivity is then equal to the absorptivity for making temperature measurements with a conventional pyrometer at the same wavelength and location as the measurements with the laser. The Pyrolaser operates in the near infrared (NIR) at 865, 905 or 1550 nm, with a narrow bandwidth (10-15 nm) [8]. The accuracy for grey bodies is similar to the multiple wavelength technique used in the FAR spectropyrometer (see Table 2). Shiny surfaces are a problem for this technique also, so an optional irradiance sensor can be added to increase measurement accuracy. The Pyrofiber pyrometer has a budget price somewhat less than the FAR IR pyrometer (15 000 to 19 000 USD in 2002).

Table 2. Emissivity independent IR pyrometers for surface temperatures.

Name	Temperature range (C)	Target distance (m)	Accuracy (grey body)	Method
1. Pyrolaser*	600-3000	0.2-10	±3°C	laser
2. Pyrofiber*	250-3000	0.15-2.4	±3°C	laser
3. FMP2**	800-2500	0.15-6 m	0.15% or 3°C at 2000°C	500-1000 nm spectrum
4. FMPI**	300-2000	0.15-6 m	0.15%	1100-1700 nm spectrum

** The Pyrometer Instrument Co. at: http://www.pyrometer.com
** FAR Associates at: http://www.pyrometry.com

AvestaPolarit in Avesta has made trials in their continuous annealing furnace (KBR) independent of this project with the laser based surface emissivity pyrometers from Pyrometer Instrument Co. Two models have been tested, the PF865 (operating at 865 nm) and the PF1550 (operating at 1550 nm). The KBR mill anneals stainless steel strip with varying emissivity (of about 0.2), so that an IR pyrometer with emissivity compensation is important for accurate surface temperature measurements. The instrument has performed well with good temperature measurements. It is important to note that the surface emissivity measured by the laser is at the specific wavelength used for temperature measurements, so the emissivity obtained is not necessarily the same as the proper emissivity for a conventional IR pyrometer operating over a broad IR spectrum.

Another variation of IR surface temperature pyrometry is to use fibre optic cables to carry the signal to and from the sensor. The IR pyrometer can then be placed further from the furnace. This technique has been used for temperature measurements of slabs from a steel caster with 15 m long fibre cables [9]. A tube or channel can be used to exclude interference from radiation and dust between the IR pyrometer lens and the measurement object. IR pyrometers operating with wavelengths from about 2-3 microns are designed for measuring the temperature of metals or steel slabs and more information about these systems can be obtained from instrument suppliers. Local temperature measurements can be made of a given object, if a surface with a known emissivity is placed at the furnace end of the optical fibre. Knowing the emissivity gives highly accurate surface temperature measurements.

2.2 IR Gas Temperature Pyrometers

Average gas temperature measurements can be made using a IR pyrometer operating at a wavelength corresponding to the emission of combustion products, such as CO_2 gas radiation (at 4.26 or 4.5 microns). This technique requires combustion gases, since air does not have strong IR emission peaks. All fossil fuels generate CO_2 when burnt, so the method is applicable to oil and propane fired furnaces, but not for electrically heated furnaces. The gas temperature measured is the radiation temperature of the CO_2 gases in the field of view of the lens, therefore choice of lens and placement is important. The Heitronics KT-19 model is stated to have up to 530 different field of views available, by choosing from 18 standard lenses [10]. The field of view increases with distance from the lens, so the greatest gas volume is furthest from the lens. The spreading of the field of view with distance is conically shaped, and typically expressed as a ratio, as 30:1, which means that the beam enlarges to a diameter of 1 meter for a path length of 30 meters. Therefore one IR pyrometer does not give the true average gas temperature across the furnace, if there are large temperature gradients. For example, one side of the soaking zone can be hotter, so that the trailing end of a billet is hotter than the leading end. In this case, two IR pyrometers should be placed on opposite sides of the furnace to measure this temperature inhomogeneity.

An ordinary IR pyrometer can be converted to a CO_2 gas temperature pyrometer with a suitable filter and re-calibration for the radiation spectrum, since then only radiation from the CO_2 gas enters the pyrometer instead of a wide bandwidth of radiation from everything in the field of view. The high cost of these specialty filters makes converting existing pyrometers rather uninteresting. An IR band-pass filter 25 mm in diameter for CO_2 radiation with a CWL at 4.5 microns was available from Janos Technology Inc for $570 in 2002 (Part nr. FXBP-0450 [11,Jano]).

Temperature inhomogeneities can also give problems in other ways. A local hot spot in the field of view (for example, caused by a flame) gives such high IR radiation, that the temperature measurement primarily reflects the flame temperature. Likewise, the peak temperature is the maximum temperature measured by the instrument over a time interval. Quick response times are possible (30 ms), so it is possible to detect temperature fluctuations lasting less than 1 sec. Average temperatures are more important than fast, instantaneous temperatures for controlling large furnaces, so the response time should be slow when used as an input to a furnace controller.

Anything that blocks the view of the lens (as soot or dust), air infiltration (less CO_2 to measure temperatures) or large variations in gas temperature with time can make the average temperature signal too noisy to use directly in a control system. Tests by one instrument manufacturer [12] suggests from boiler tests that the signal from the peak temperature hold function over a 10 s interval is sent to the furnace controller where it is smoothed before using in the control system. The IR pyrometer system has proven so reliable for boilers that it can replace the use of retractable temperature probes (as suction pyrometers).

Table 3. Performance of IR gas temperature pyrometers (see also Appendix 2).

Manufacturer	Model	Max temp	Accuracy	Comments
Heitronics GmbH Wiesbaden, Germany Rep. Pentronic www.pentronic.se	Heitronics KT19.61	2500°C	±0.5°C + 0.7% of reading	±0.1°C resolution 30 ms to 10 s response time
JNT Technical Services Inc. Little Ferry, NJ www.infra-view.com	Infra-View	1649°C	±1% of reading	100 ms up to 55 s with averaging and peak hold
E2Technology Corp. Ventura, CA www.mikroninst.com/E2T	Pulsar II	1650°C	±1% of reading or ±5°C	30 ms to 1 s standard response times
LAND Infrared Dronfield, UK	CD1	1800°C	±1% of reading 600-1500°C	Furnace trials were made at Sandvik and SSAB with the CD1

2.2.1 Trials with the LAND CD1 Pyrometer at Sandvik Steel

A LAND CD1 combustion gas pyrometer was loaned for trials at Sandvik Steel in Sandviken. The instrument has a good range (400-1800 °C) and a competitive price (see Appendix 1). The pyrometer requires a cooled mounting bracket to avoid excessively high temperatures if mounted in a hot area. The CD1 gas pyrometer was tested in 3 positions in the hot strip mill furnace at Sandvik Steel in June 2002 [3, earlier]. Holes were drilled in the side of zone 2 at two different levels relative to the flames, one near the stock and the other near the burner flame, plus a third position in the convective zone (see Figure 1). The PC logging system from the CD1 pyrometer to the Tracker 3000 data logger did not work properly, so most of the data was on paper strip.

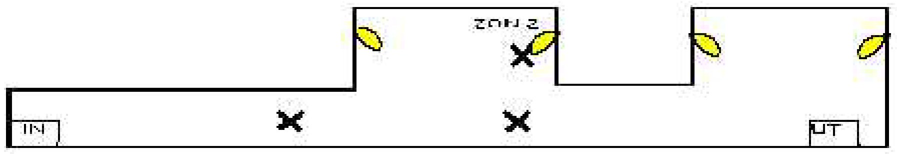

Figure 1. Sketch of the strip mill furnace at Sandvik with the measurement positions.

Temperature measurements at the upper measurement position in zone 2 are shown in Figure 2. The time axis is vertical in this figure. The burner output was at 45 % of the maximum flow at the start of the test, then the fuel flow was decreased to 0 % for about 2 minutes and up to 100 % for a few minutes, before returning to the original level. The thermocouple in the ceiling of this zone initially registered ca 1060 ºC, while the combustion gases were ca 130 ºC hotter. The gas temperature follows the expected drop and rise with burner output much better than the thermocouple. A similar test was made in the lower section of zone 2 with similar results, except the maximum gas temperature was ca 50-60 ºC lower than the ceiling thermocouple (Figure 3).

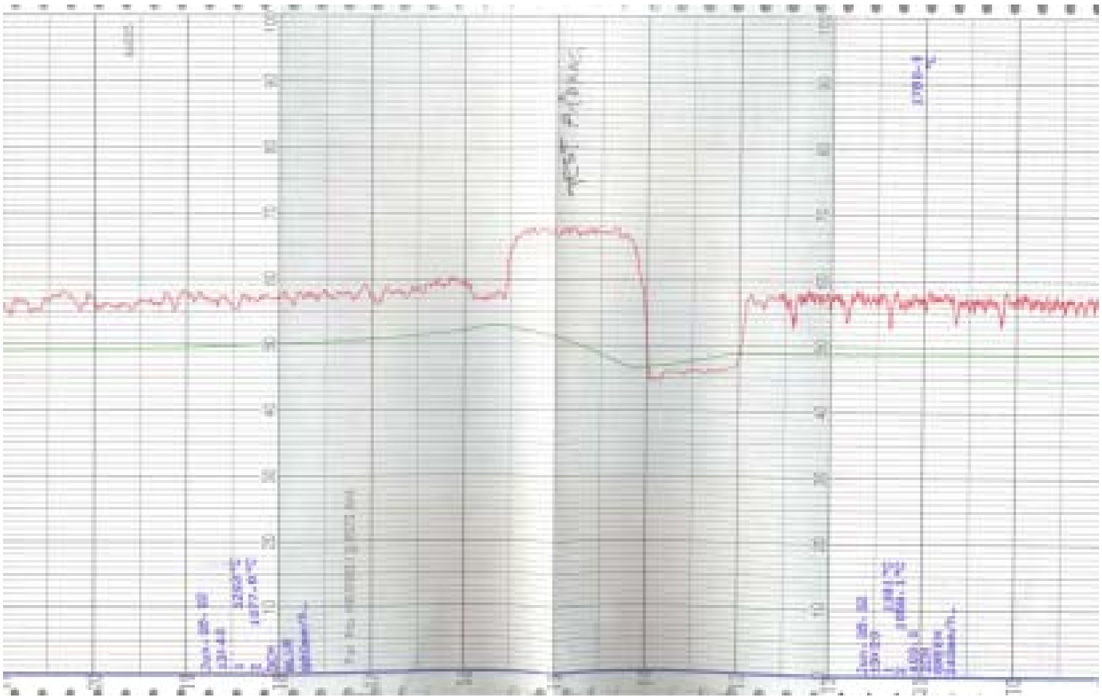

Figure 2. Combustion gas temperatures (wavy red line) compared with the ceiling thermocouple in the upper section of zone 2 with varying burner output from 0 to 100 %.

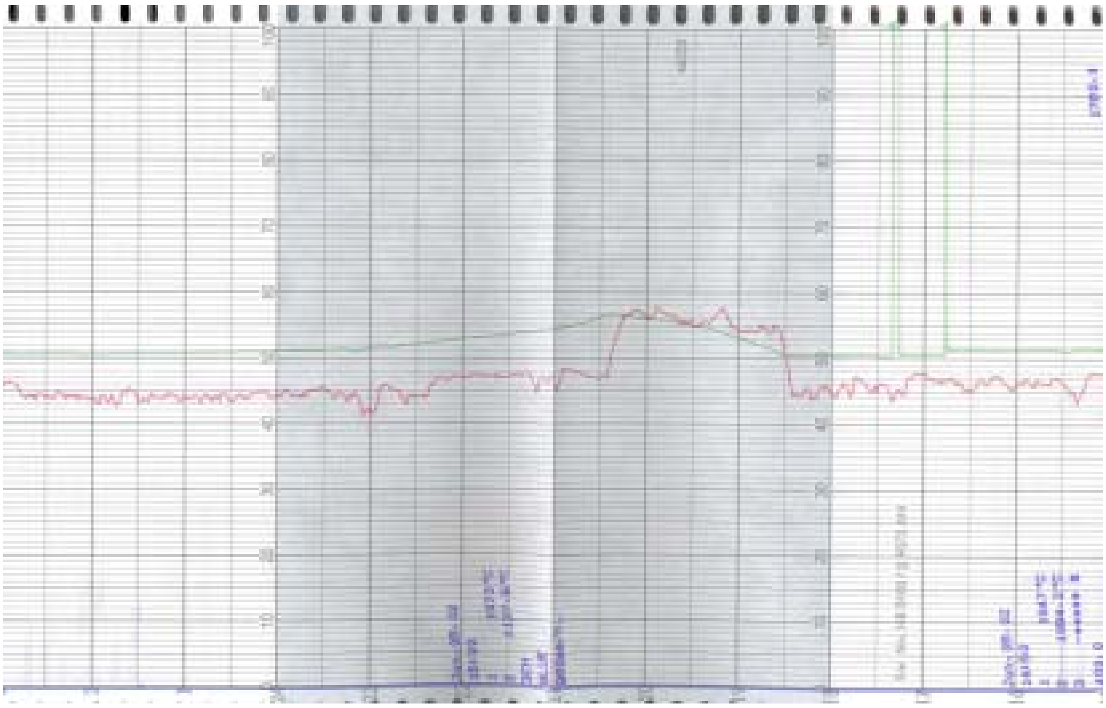

Figure 3. Combustion gas temperatures (wavy red line) compared with the ceiling thermocouple in the lower section of zone 2 with varying burner output from 0 to 100 %.

Another test was made varying the burner output and the furnace atmosphere at the upper position in zone 2. The furnace atmosphere was varied by adding only combustion air in 4 of the 9 burners in zone 2 (Figure 4). The drop in gas temperature at 15:02 is probably due to the drop in furnace temperature rather than the lower CO_2 concentration, since the instrument is designed to operate well down to 4 % CO_2.

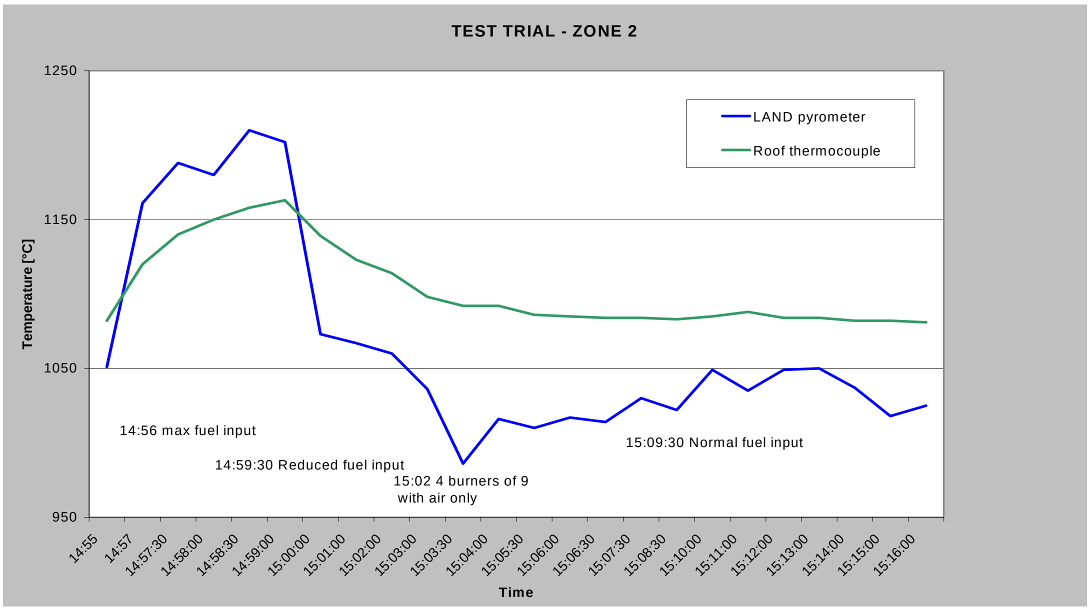

Figure 4. Test with varying burner output and furnace atmosphere at the lower measurement position in zone 2.

The CD1 pyrometer was moved to the convective preheating zone. A brief test was made by increasing the burner output then reducing the burner outputs while monitoring the temperatures as shown in Figure 5. The difference between the wall thermocouple and the gas temperature is greater than in zone 2, that is, ca 250-300 °C, and it increased to about 400 °C during the test. Note that the measurements are made at about the same height as in zone 2, but that the combustion gas temperatures in the preheating zone are higher than for the wall thermocouple which is the opposite of that observed at the lower position in zone 2 (see Figure 3). The explanation for this difference is probably related to the effect of the burner flames in zone 2. A thermocouple measures the temperature based on the overall heat transfer at the tip of the thermocouple, and the heat transfer by radiation is strongly influenced by the T^4 factor for radiation from the flames. The preheating zone thermocouple loses heat by radiation to the cool slabs. Properly placed radiation shields for thermocouples should help reduce unwanted radiation effects when attempting to measure gas or surface temperatures.

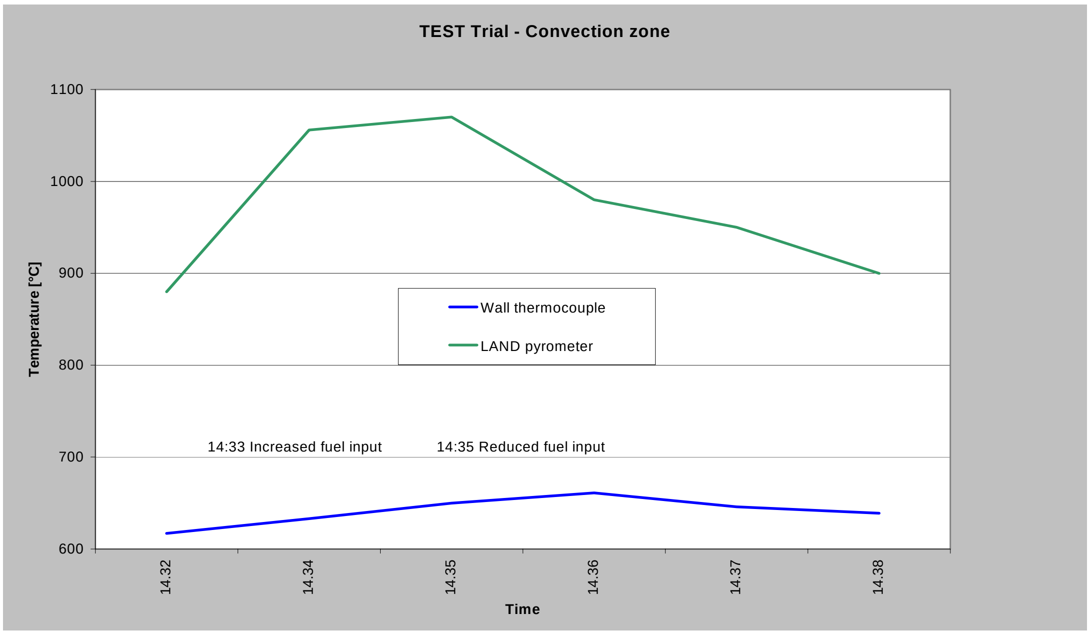

Figure 5. The effect of varying the burner outputs on the gas temperatures in the convective zone.

Temperatures in zone 2 were measured with a suction pyrometer for comparison with the results of the LAND CD1 combustion gas pyrometer. Both instruments could not be used simultaneously, so there was a delay time to switch pyrometers. Plus the suction pyrometer measures the gas temperature at a point, while the gas pyrometer measures the temperatures in the field of view. Figure 6 shows that the gas temperature with the suction pyrometer is about 60-75 ºC under the zone thermocouple measurements. Similar tests in Figure 3 showed a temperature difference of about 50-60 °C, or potentially about a 10-20 °C difference between the temperatures recorded by the two pyrometers. Simultaneous measurements with the two instruments at the same position are not possible, since there is a cooling effect in the furnace for the water-cooled sampling pipe. These tests confirm that the gas temperature in the lower part of zone 2 is normally lower than the zone thermocouple.

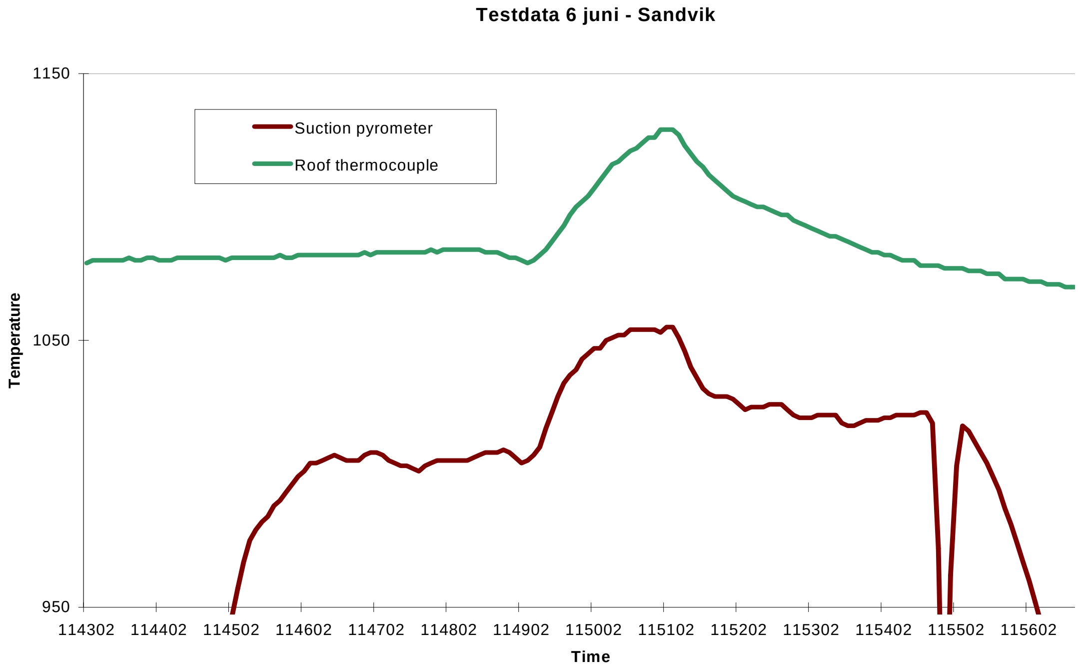

Figure 6. Temperature with the suction pyrometer at the lower position in zone 2.

The LAND CD1 pyrometer worked well in these trials, and appears to be a good addition to conventional temperature control in reheating furnaces using wall thermocouples and IR pyrometers outside the furnace. One of the most promising applications is to use the gas temperature signal in the furnace control system, for example, FOCS-RF, since the combustion gas temperature is normally estimated from the wall temperature using a burner output bias.

2.2.2 Trials with the LAND CD1 Pyrometer at SSAB Tunnplåt

The CD1 pyrometer was also tested at SSAB for furnace gas temperatures. The pyrometer gave gas temperatures, which could be about 100-200 °C lower than the estimates used by the FOCS control system (see Figure 7 below). This is similar to the data obtained from trial with the TDLAS (see later section of this report). The same hole in zone 1 was used for the CD1 gas temperature pyrometer as the TDLAS, so the cooling effect of the slabs could be part of the reason for the lower gas temperatures from the measurements. The gas temperature should be measured at other positions in the furnace, since highly accurate gas temperatures could be a method for improving the predictions by the FOCS program. Better stock temperature predictions can save energy and improve productivity, therefore the difference in gas temperatures are worth further investigation.

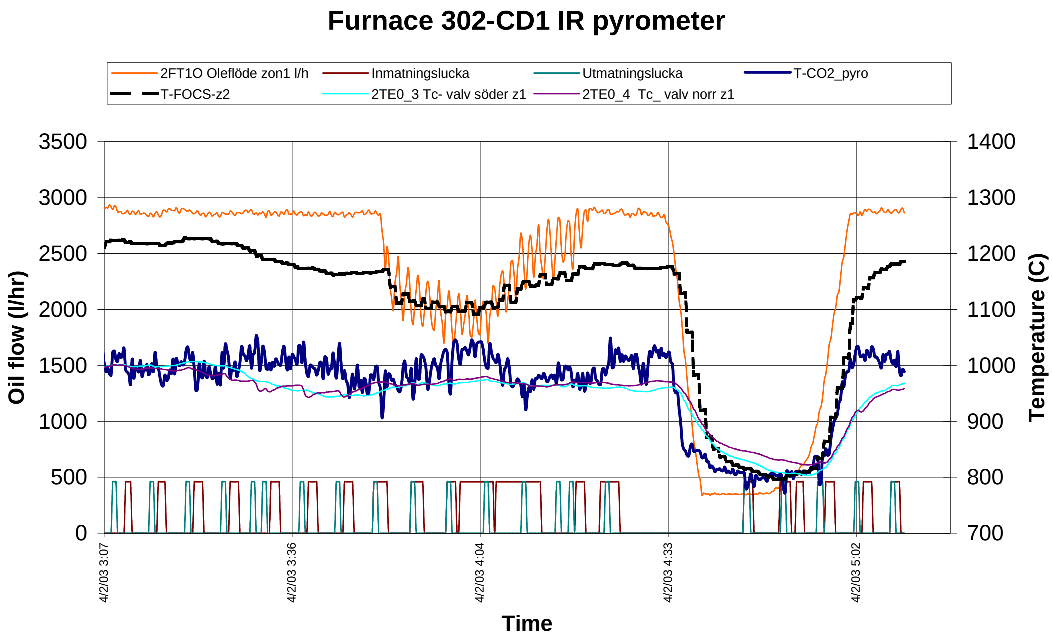

Figure 7. Deviation between FOCS and measured gas temperatures

The ultimate goal of better furnace gas temperature measurements is to use them in the Fuel Optimization and Control System (FOCS) instead of an estimated gas temperature using a bias factor for the burner output. A furnace trial at SSAB with the LAND CD1 pyrometer was proposed by MEFOS to investigate this problem. JK5151 chose a simpler trial supervised by SSAB, potentially with the cooperation of MEFOS through other project work at SSAB. The other project work has been delayed, and tests with using the gas temperature in the FOCS system requires considerable stock temperature calibration work beyond the time frame of this project.

In summary, advantages of IR pyrometry include accurate, non-contact, in-situ, average gas temperature measurements for a reasonable price. IR pyrometers are in the same price range as what might be expected for suction pyrometer which give local gas temperatures using a thermocouple, but have high operational costs. For example, the Heitronics KT19.61 is a top line instrument with a price range of about 50-60 kkr.

Disadvantages include the spreading of the field of view, interference of flames and soot, and in some cases cooling requirements. A true average gas temperature linearly across the furnace is not obtained (rather the average gas temperature in the field of view). An IR pyrometer is a sensitive electronic instrument compared to a thermocouple. If the environment is exceptionally harsh with high temperatures, then water cooling or remote instrumentation with a fibre optic cable can be required.

3 TDLAS - TUNABLE DIODE LASER ABSORPTION SPECTROSCOPY IR

TDLAS systems are being marketed in Sweden for in-situ oxygen gas analysis and gas temperature measurements, and both parameters, are of interest for controlling reheating furnaces. The TDLAS technique is primarily designed for gas analysis, with temperature measurements a secondary feature for combustion monitoring (when oxygen or water vapour are present).

3.1 Operational Principles for TDLAS

In a TDLAS instrument, a laser diode is “tuned” or adjusted to the wavelength where the gas being measured absorbs infrared radiation (or light). 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 "tune" or scan the output of the diode through the wavelengths corresponding to the absorption peak [13].

Gas temperatures are measured using oxygen peaks around 0.76 microns in the instruments listed in Table 4. The effect of temperature on peak intensity is not known sufficiently theoretically, so the TDLAS technique requires experimental selection of absorption peaks and calibration of the temperature range desired. Research at MEFOS investigating TDLAS for high temperature measurements reported an accuracy of ± 25 °C for 700-1500 °C after calibration of a LDS 3000 instrument using high oxygen concentrations [14]. The temperature sensitivity of the absorption line strengths often decrease with increased temperature, so temperature readings above the manufacturers calibrated temperature range can have a greater inaccuracy.

Table 4. Scandinavian manufacturers of TDLAS equipment [15].

Manufacturer	Model	Temperatures	Accuracy	Comments
NEO A/S Skårer, Norway www.neo.no	LaserGas O_2 Monitor	to 1500 °C	Instrument drift <4% of range	Oxygen and temp
Siemens Laser Analytics Göteborg, Sweden www.altoptronic.se	LDS 3000	700-1500 °C	<5% at 900°C	O_2 or H_2O and temperature
OPSIS AB Furulund, Sweden www.opsis.se	LH515	0-1400 °C	±2% of span	Oxygen and temp

Data in reported from the University of Toronto for the LasIR model LCM-03 manufactured by Unisearch Associates Inc using two closely spaced water vapour peaks (at 1.5778 and 1.5781 microns) gave much more noise with a σ (STD) of 36 °C (± 2σ = ± 72 °C) [16]. The test conditions were not as ideal, using a multiple pass detection cell for a burner flame in the Toronto test versus a special furnace at

MEFOS, and widely varying gas concentrations (3-27 % H_2O) versus a high oxygen concentration at MEFOS (about 20 % O_2).

3.2 Trials with TDLAS

Gas temperature measurements are possible using Siemens Laser Analytics LDS3000 oxygen analyser (or TDLAS). It was configured to measure over 3 paths simultaneously. Two zones were monitored in the oil-fired furnace 302 (zone 1 and 5). These trials using the TDLAS technique were made within another JK project (JK5149), and additional details of the trials can be found elsewhere [17]. An example of the temperature data is given in the figure below. The instrument worked well with about 4 % excess oxygen on the 12 m path (60 % oxygen-meter), but began full scale oscillations when the oxygen absorption peaks got too weak.

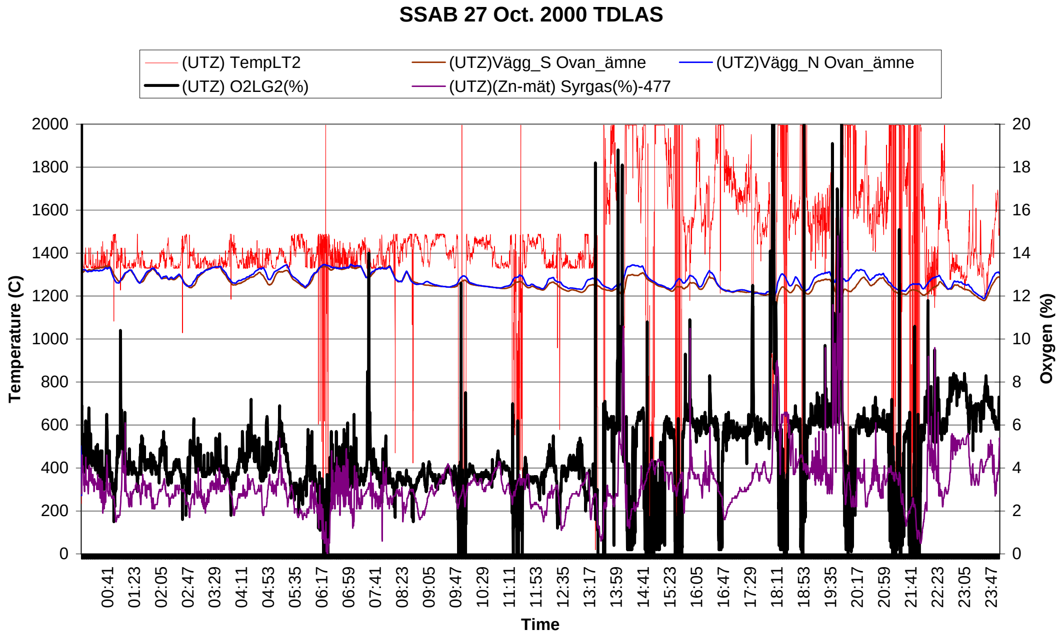

Figure 8. Instability in the simultaneous measurement of the excess oxygen and temperature in the soaking zone of SSAB Furnace 302 at low levels of excess oxygen.

A closer look at the period of instability at about 6:20 shows that the oxygen concentration dropped below about 2 % with a gas temperature of about 1400 °C (see Figure 9). The measurements for temperature and oxygen concentration are not independent, so both measurements are unreliable when the temperature readings become unstable. The TDLAS simultaneously analyses the relative peak intensities for both temperature and the oxygen concentration in the software program. The software program can be changed to only analyse the oxygen concentration, with an external gas temperature signal, but then the instrument becomes only an oxygen analyser.

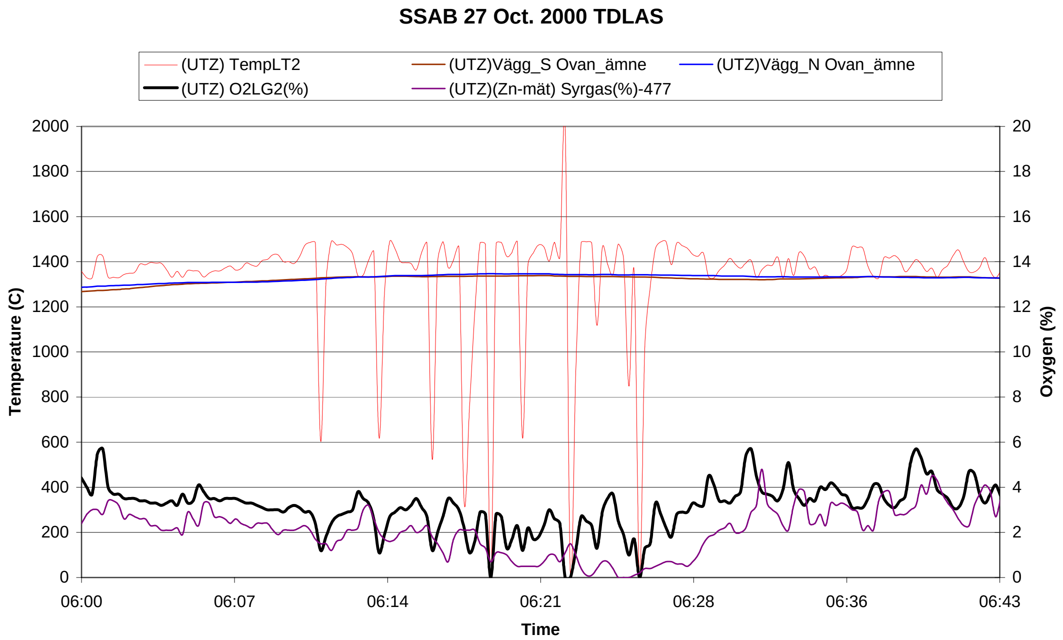

Figure 9. An expanded time scale for of the instability in the simultaneous measurement of the excess oxygen and temperature in the soaking zone of SSAB Furnace 302 at low levels of excess oxygen at 6:20.

The most difficult conditions are in zone 5 with high temperatures and sometimes low oxygen concentrations. A relatively good period is seen about 1:00-4:00 in Figure 8, when the oxygen concentration was relatively high (4 % O_2) in zone 5. The furnace temperature shows sudden dips when the oxygen concentration went below a certain level (approximately 2 % O_2). This loss of the temperature signal with low oxygen concentrations makes it unsuitable for a control signal. The temperature signal was generally good in zone 1 (see Figure 10). It is interesting to note that the gas temperature was lower than the ceiling thermocouple temperature in this figure. This is similar to the data from the preheating zone in the Sandvik trial.

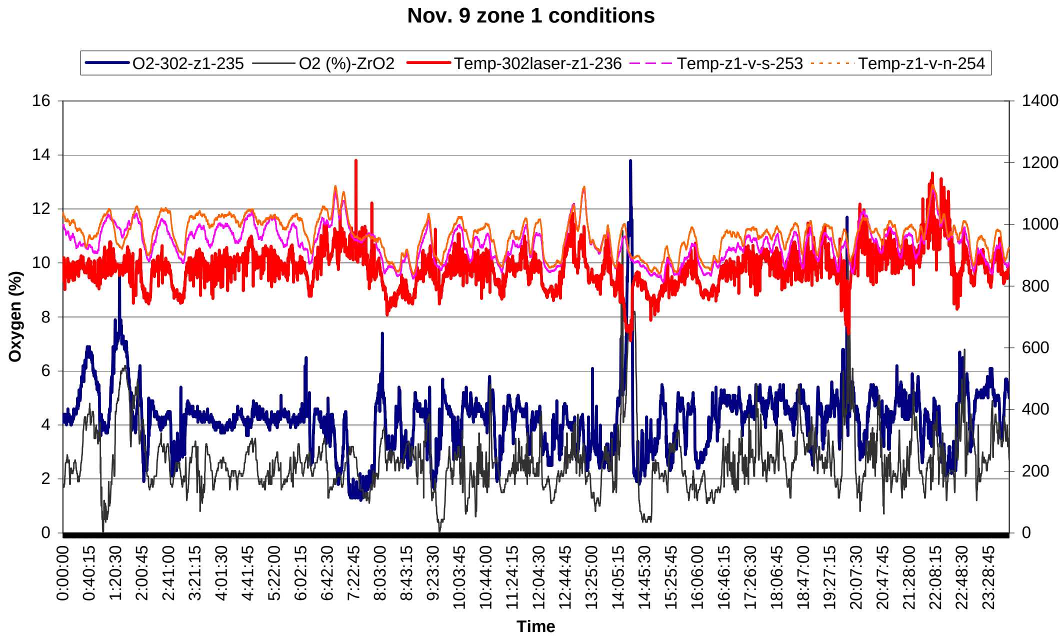

Figure 10. Good measurement stability with the TDLAS in zone 1.

The minimum percent oxygen for which temperature measurements are reliable depends on the installation conditions. The absorption peaks depend on the number of oxygen molecules available for detection, which is a function of the path length, gas temperature, beam diameter, etc. The path length in this furnace was 12 m, which improves the sensitivity over typical laboratory conditions.

A trial measuring the stock temperatures using an insulated data logger was made on December 6, 2000 while the TDLAS was monitoring the gas temperatures and excess oxygen. The gas temperatures during the trial are shown in Figure 11 below. The gas temperatures in zone 1 were stable, while the gas temperatures in zone 5 were unstable. The TDLAS temperature measurements had spurious temperature spikes that correlate well with discharge door opening cycles. They apparently are due to instrument error when cool infiltration air entered the furnace with the discharge door open.

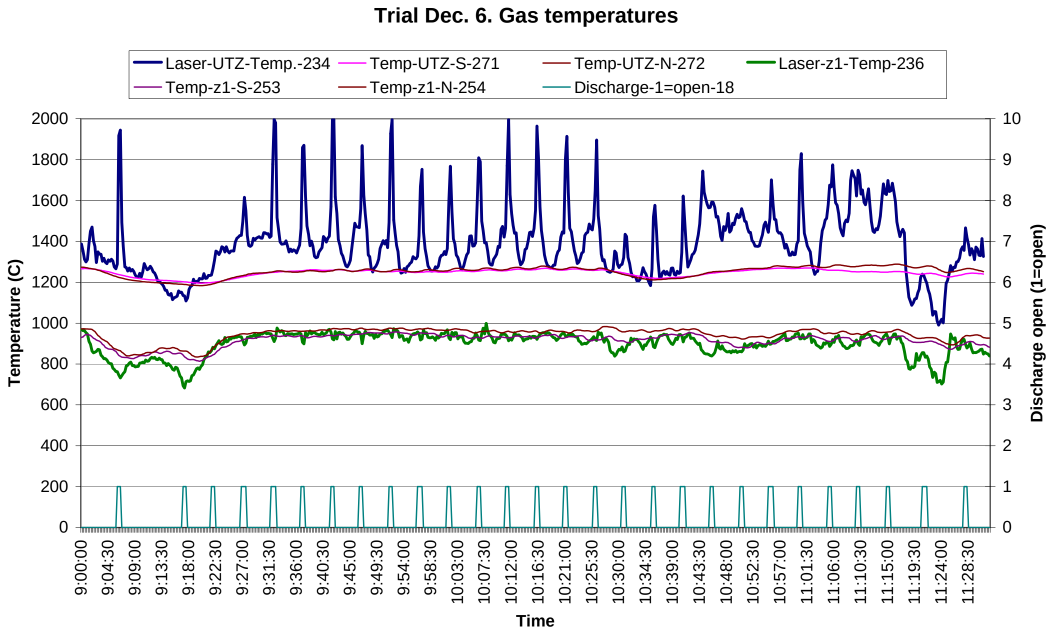

Figure 11. Gas temperatures in zones 1 and 5 during a data logger trial.

Steeltemp was used to predict the stock temperatures, similar to the predictions made in the FOCS control system. The gas temperatures are estimated in the FOCS program using a bias factor from the burner outputs (Figure 12). The gas temperature in zone 1 was about 950 °C versus a Steeltemp temperature around 1200 °C. The gas temperature was measured near the slabs which have a cooling effect, so part of the difference in gas temperature is due to the measurement position. Note how stable the gas temperature measurements were in zone 1 versus zone 5. The TDLAS technique is better suited for measurements with the lower gas temperatures and higher excess oxygen levels of zone 1. The gas temperature predicted for zone 5 was about 1350-1400 °C, which is quite close to the minimum values in the TDLAS measurements. The top and bottom slab surface temperatures measured with the data logger converge nicely before discharge (Figure 13) as in the Steeltemp model.

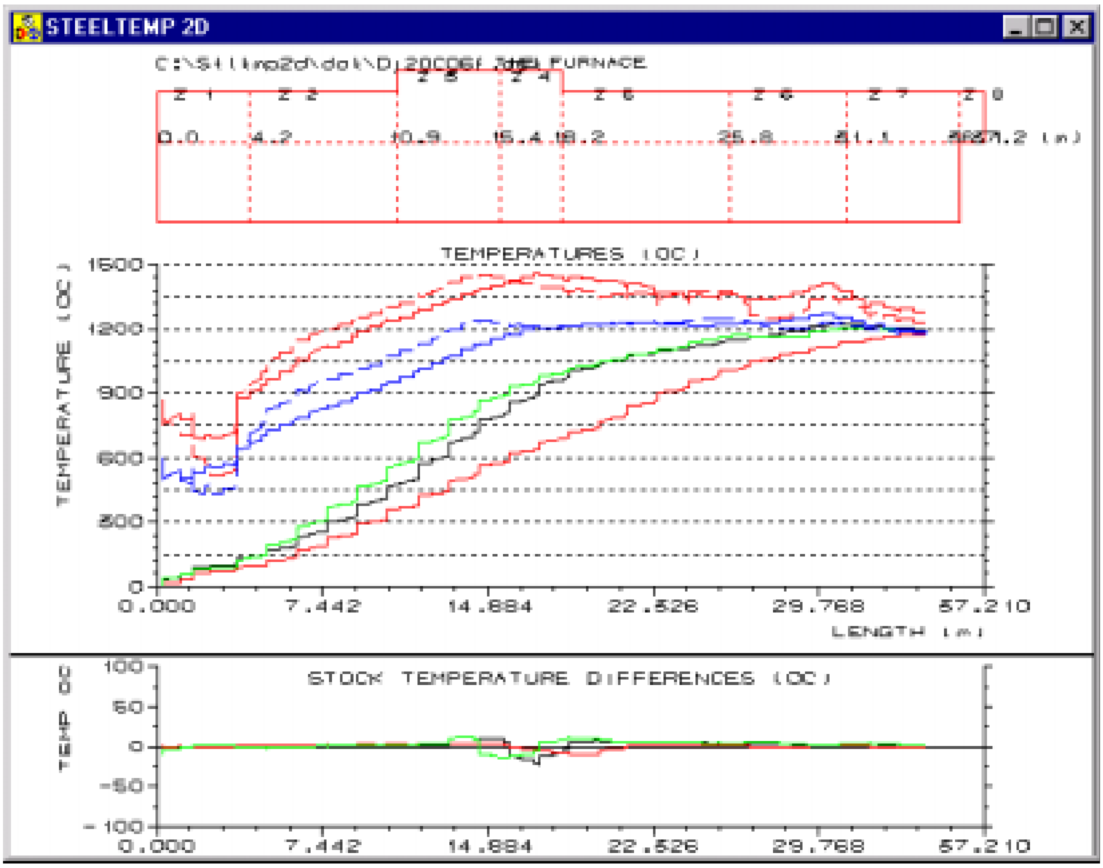

Figure 12. Gas and stock temperatures in the Steeltemp model of Furnace 302 at SSAB.

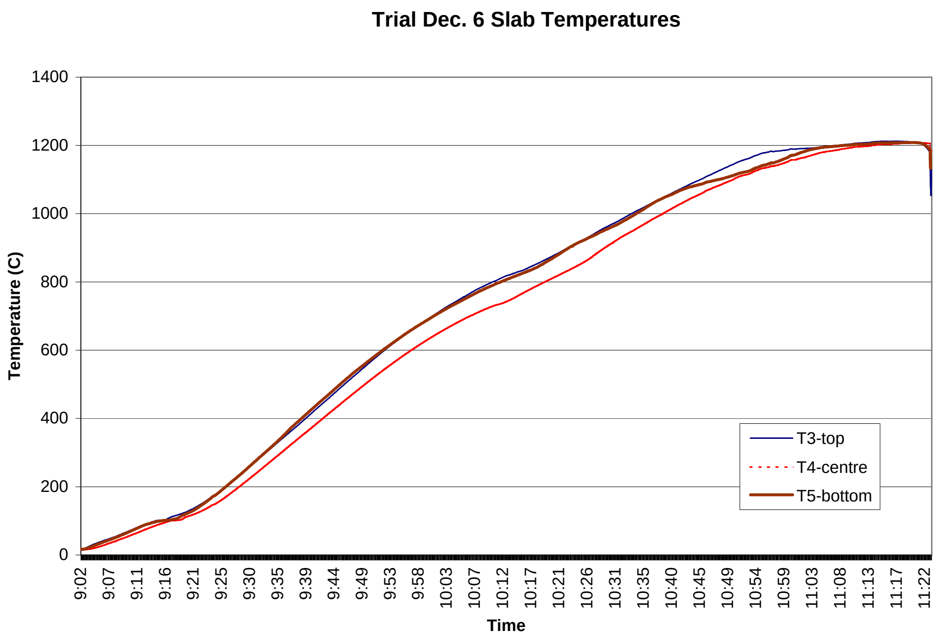

Figure 13. Thermocouple temperatures at position 4 (middle) of the test slab at SSAB, with the top, centre and bottom slab temperatures.

Advantages of TDLAS include the true, in-situ average gas temperature across the path chosen (since a laser beam has very little beam enlargement), simultaneous gas analysis and fast response time. The benefits of improved gas analysis can justify the installation of TDLAS for some applications, and temperature measurements are a standard feature for some TDLAS instruments (LDS 3000).

Disadvantages of TDLAS for temperature measurement include the high initial cost, high operational costs for N_2 purge gas and low temperature accuracy at low gas concentrations. The prices of TDLAS instrumentation vary widely. The LaserGas O_2 Monitor is a low cost model at about 200 kkr with temperature and oxygen measurements (in 2003) versus about 400 kkr for the LH515. The laser wavelength is chosen specifically for a given gas, so that normally separate lasers are required for different gases. The LH515 can have several lasers in the same instrument, but the cost of each additional laser is high.

4 ACOUSTIC PYROMETERS

Acoustic pyrometers measure the temperature of gases based on the temperature dependence of the speed of sound. The speed of sound varies by the square root of the absolute gas temperature. This technique gives an average temperature over a known path length if the gas composition is known and constant. Simple acoustical pyrometry uses the time of flight data for the first wavefront to reach the receiver. This is adequate for an average gas temperature for one path. The wavelengths can be large, for example, assuming a sound velocity of 880 m/s at a frequency of 500 Hz gives a wavelength of 1.8 m. Bursts of air can be the source of sound, giving an easy to install, low-maintenance instrument. Multiple paths can be chosen, which can be analysed to give 2D isothermal maps of furnace temperature difficult to produce by other means for gas temperatures of 1650°C [18]. Many commercial acoustic pyrometers are available, for example, the Boilerwatch from SEI or CSI AP106 from Stock Equipment (see Table 5).

Table 5. Performance of acoustic pyrometers.

Manufacturer	Model	Max temp	Accuracy	Comments
SEI Inc. Sparks, Nevada www.sciengr.com	Boilerwatch	1927°C	<1.5%	1-24 paths 20 m possible
Stock Equipment Co. Chagrin Falls, Ohio www.stockequipment.com	AccuTemp (CSI AP106)	2204°C	±25C (at 1370°C)	1-7 paths/trans. up to 30.5 m long 280 l/min air at 5.5 bars
Codel Int´l Ltd Bakewell, UK www.codel.co.uk	Pyrosonic II	2000°C	±2% (±50°C)	1 path up to 8 m uses 1 l/min air @ 5 bars
Bonnenberg + Drescher Aldenhoven, Ger. www.budi.de	agam MMP	1927°C	<1.5%	1 to 24 paths uses 5.5-8.3 bar air for sound

Advantages of acoustical pyrometry include simple and rugged equipment for industrial environments, multiple paths from a single transmitter for a minimum number of holes in the furnace walls for 2D temperature mapping, low operating costs and proven technology. One transmitter can have 6 receivers, so that 8 combination receiver/transmitter sensors can give 24 paths. These devices have been proven in large utility boilers to monitor the location of high combustion rates (or the "fireball") to prevent excessively high temperatures at the boiler tubes. Temperature mapping in steel reheating furnaces could reduce the risk of overheating the surface of the steel. Peak furnace gas temperatures can also be correlated with NOx production to avoid operational conditions that generate excessive amounts of NOx.

Disadvantages of acoustical pyrometry include the lower accuracy and higher cost of equipment relative to IR pyrometry for a single measurement path. The speed of sound depends on the gas composition and combustion gas flow, so complete combustion (or gas analysis) is desirable, with relatively low gas flow velocities in the measurement zone. Some of these problems can be compensated for by adding pitot tubes to measure local gas velocities and thermocouples for local temperatures. A budget price for a single path AccuTemp unit which includes one transmitter, one receiver and the control system is about $25,000 (ca 250 kkr) at the USA factory, while a temperature profiling system including two transmitters, six receivers and the control system which would cost around $55,000 (ca 550 kkr) [19]. Additional costs include transportation, import fees, installation, and integration into the control system. A hole in the furnace wall is required for each transmitter or receiver (a 45 mm diameter penetration into the furnace for the transmitters and a 15 mm diameter penetration for the receivers).

5 MICROWAVE TECHNOLOGY

Microwaves can be used for gas temperature measurements. The Jet Propulsion Laboratory (JPL, [20]) has developed a microwave air temperature profiler, MTP/DC-8 which measures the microwave thermal emissions of oxygen molecules at 55-59 GHz to derive the air temperature as a function of the altitude. An air temperature profile can be obtained in 14 s with an RMS uncertainty in accuracy of 1-2 °C depending on the path length which are measured in km, for example, < 2 °C uncertainty for altitudes from 8-17 km with an altitude accuracy of about 0.5 km. The technology has not been developed for furnace temperature measurements, but the principle should be applicable, that is, to use higher frequency radiation (absorption or emission) in the microwave region instead of the infrared region for temperature measurements. MEFOS is currently involved in research into the use of microwaves for gas analysis in steelmaking, and advantages of using microwaves include complete isolation of the instrument from the flue gases, low sensitivity to dust and measurement of average gas properties [21].

6 THERMOCOUPLES AND SUCTION PYROMETERS

Thermocouple techniques were reviewed in both the general literature survey [22,Niska] and a review on thermocouple techniques [23,Magnus]. It is interesting to note that there has been little published in the past 10 years on thermocouple techniques for gas temperature measurements, while in-situ and non-intrusive methods have been widely investigated.

True gas temperatures can be obtained with thermocouples, by using multiple thermocouple techniques or a suction pyrometer. Suction pyrometers are expensive to operate since the sampling tube needs to be water-cooled, and large amounts of compressed air are typically used by the furnace gas ejector to sample the furnace gases at a high velocity. An alternative to conventional suction pyrometers is the "microsuction pyrometer", which can be used without cooling.

6.1 Thermocouples

There have been advancements in the base metal type thermocouples, with Type N replacing the older Type K (chromel-alumel) and Type J thermocouples. One of the greatest problems with thermocouples is their degradation in performance with time at high temperatures. Oxidation of the wires causes inaccuracies, which depend on the wire size and the time at temperature. Reducing combustion gas atmospheres are detrimental to type K thermocouple, since the Chromel wire can preferentially lose Cr at the surface giving a green coating or green rot. Green rot causes the thermocouple signal to rapidly give negative drift (low temperatures readings). Under oxidising conditions the Alumel wire tends to oxidise faster than the Chromel wire giving positive drift [24]. A 3.3 mm dia wire Type K thermocouple heated in air showed less than a 2 °C error for 1000 hrs at 760 °C or less, but an error of 10.6 °C at 1093 °C for the same time. At 1204 °C the temperature signal drifted 11.7 °C in only 200 hrs [25]. This problem makes Type K thermocouple unsuitable for long term measurements of high temperature furnace gases.

One of the most common noble metal thermocouples is the Type S or Pt 10 % Rh-Pt thermocouple. The maximum temperature for short tests is limited by the melting point of platinum at 1772 °C, but long-term use is limited by grain growth and transport of rodium to the platinum wire at temperatures above 1400 °C. The Type B thermocouple is preferred when the temperature can exceed 1480 °C [26]. High purity alumina tubes and insulators are recommended, since silica can form silicon under reducing conditions. A comparison of the conditions recommended for the various thermocouples is given in Table 6.

Table 6. Selected types of thermocouples.

Type	Alloys	Recommended max temperature Continuous (Peak) [26]	Notes
1. Base Metals			
Type K	Chromel-Alumel	871°C (1260°C)	Cr-Ni like Type N
Type N	Nicrosil – Nisil	1250°C (1300°C)	Recommended for T > 870°C
2. Noble Metals			
Type S	Pt-Pt/10% Rh	1482°C (1760°C)	
Type B	Pt-Pt/30% Rh	1700°C (1820°C)	Recommended for T > 1480°C

Thermocouples are widely used for furnace wall temperature measurements, but there are many difficulties in using thermocouples for gas temperature measurements. A simple thermocouple has problem with measuring accurate gas temperatures due to temperature inaccuracies because of heat losses at the measurement point of the thermocouple due to convection, conduction and radiation. A highly turbulent gas flow increases the heat transfer to the thermocouple, and reduces errors due to conduction and radiative losses. Improving convective heat transfer is the principle used in suction pyrometers to give more accurate gas temperatures. A rule thumb is that the conduction losses are insignificant if the length of the thermocouple is 200 times the diameter [27]. Another alternative is to place the thermocouple parallel with the gas flow to avoid large temperature gradients. Radiative errors can be large if the temperature of the gas is much different than the wall or surface temperatures. Experimental trials to determine the magnitude of the errors associated with simple thermocouple methods was the topic of a trial at SSAB when the IR pyrometer is available to record the true gas temperature.

6.2 Suction pyrometers

Suction pyrometers draw the hot combustion gases past a thermocouple at a high velocity to reduce the error in gas temperature measurements. Radiation shields minimise the thermal effects of radiation. Suction pyrometers are still one of the best industrial tools for measuring combustion gas temperatures, for example, they are useful for temporary gas temperature measurements at a particular location or for calibration of other temperature measurement equipment.

Large water cooled suction pyrometers with ceramic probes can be obtained from the IFRF with Type S or Type B thermocouple which allow combustion gas temperature measurements to 1800 °C. The minimum gas velocity in the probe should be 50 m/s, but velocities above 100 m/s are preferable. A velocity of 150 m/s in the

IFRF probe gives a time of 3 min. to reach an equilibrium temperature in the thermocouple. The temperature error can still be 3-7 °C with a gas velocity of 200-300 m/s as reported by Chedaille and Braud [28]. Disadvantages of suction pyrometers include the high operating costs (heat losses to the probe, cooling water and ejector air), local instead of average gas temperature measurements and the probe can influence the measurement environment (due to the cooling effect of the cold outer surface).

The microsuction pyrometer has been developed to avoid many of the disadvantages of the suction pyrometer. Major disadvantages with microsuction pyrometers include their lower accuracy and more fragile construction relative to conventional suction pyrometers.

7 OTHER TECHNIQUES

7.1 Gas Temperature Predictions for Furnace Control

An alternative to measuring the gas temperature in every zone in a multizone reheating furnace is to use gas temperature measurements to generate a better model for the way the combustion gas temperature varies as the operating conditions vary. The FOCS program estimates the furnace gas temperature based on the burner power output levels. This is a rather rough estimate of the actual gas temperature, since the flame temperature is known to vary with the fuel-air stoichiometry, the combustion air temperature, etc. There is also a time delay between the change in the furnace burner conditions and a change in the wall temperature, due to the thermal mass of the furnace wall. A simple model was made to see if some of the factors known to influence the wall temperature have a significant effect in a linear regression model. A set of data for zone 1 laser gas temperatures and oxygen concentrations from the SSAB trial December 6, 2003 were tested, and the use of the measured oxygen concentration was found to have a significant effect on the gas temperature and give an improved predicted value for the gas temperature. The equation that resulted was:

$$\text{Predicted Gas Temperature} = 50.0 + 0.955\,(\text{Tc-s}) + 0.022(\text{Fuel}) - 14.4\,(\%\,O2)$$
$$r^2 = 0.75$$

Tc-s = Thermocouple temperature - south
Fuel = oil flow rate to zone 1
% O_2 = excess oxygen measured with the TDLAS

A plot of the scatter in the data is given in Figure 14. All the factors were statistically significant, since a large number of data points were used to estimate them (5760 sets of data taken in 15 s intervals over 24 hours). The gas temperature is generally greater than the wall temperature by 50 °C, and increases with higher fuel flow rate, higher wall temperature, and a lower oxygen concentration. Temporary gas temperature measurements like these, together with multiple regression modelling could give better predicted gas temperatures for use in the FOCS system.

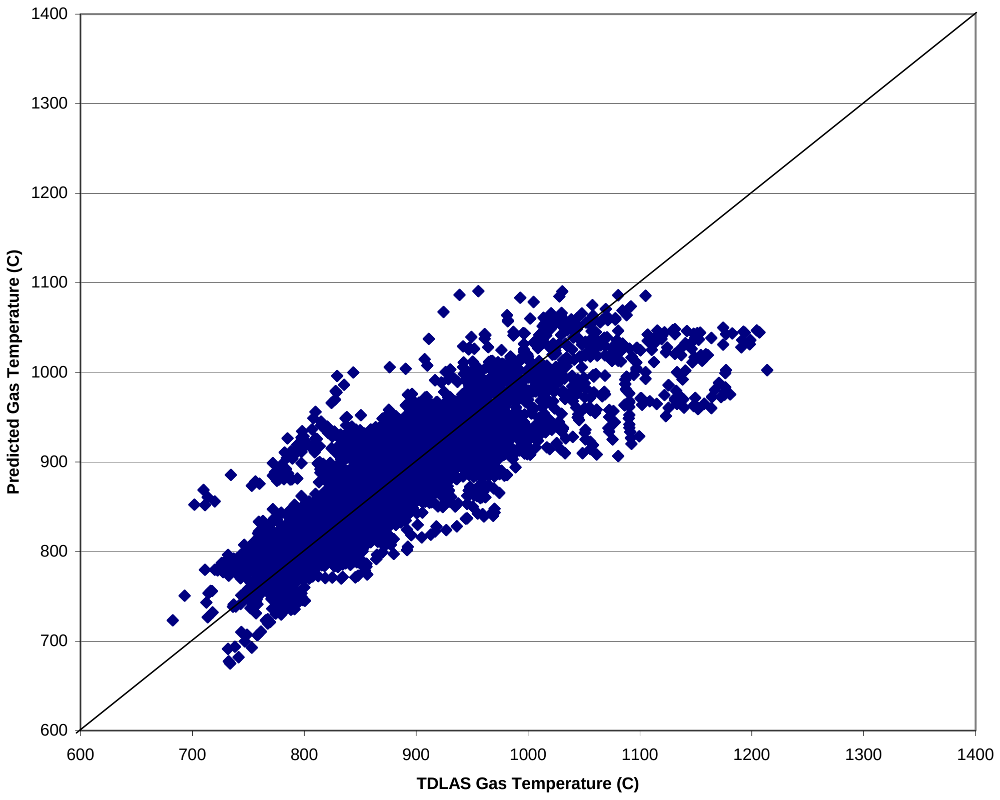

Figure 14. Predicted gas temperatures in furnace 302 versus gas temperatures measured with the TDLAS.

The low correlation coefficient and the scatter in the data are due in part to the noise in the laser gas temperature measurements. Figure 15 shows that the predicted gas temperatures follow the trends reasonably well. The furnace ceiling temperature had large swings this period, so the same technique should be tested for other operating conditions.

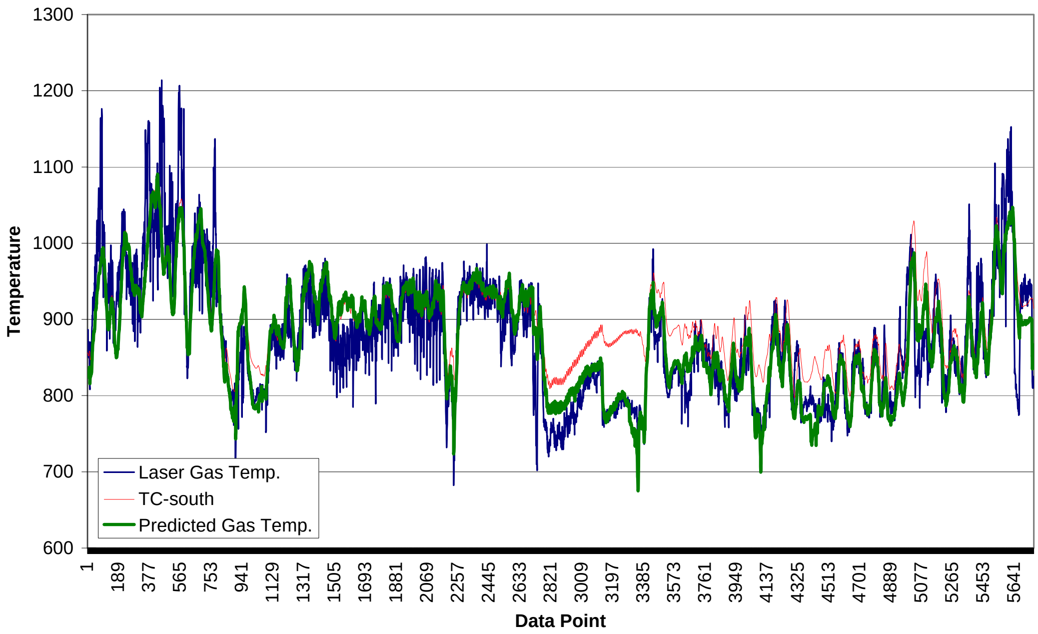

Figure 15. Predicted gas temperatures for zone 1 based on a multiple linear regression fit of the TDLAS data from December 6.

8 ENERGY SAVINGS AND INDUSTRIAL BENEFITS

Accurate temperature measurements are critical to the hot rolling of steel. The mechanical properties and the rolling process depend on uniform, well-controlled stock temperatures. Improving the process control can improve the overall product quality and save energy. The value of improved temperature control on the product quality is difficult to estimate, but poor temperature control can lead to production problems and scrap. Tighter temperature control can permit reducing the average furnace exit temperature which reduces the energy required to reheat the steel. Assuming better temperature control can lead to a lower average stock temperature and thus a reduction in the fuel consumption of 0.5 % with an energy input of 350 kWh/ton steel on an annual production of 5 Mtons steel in Sweden gives a savings of:

0.005 x 350 kWh/ton x 5 Mton/yr = 9 GWh/yr

9 RECOMMENDATIONS AND CONCLUSIONS

Commercial infrared combustion gas pyrometers for measuring average gas temperatures were tested with promising results. They offer the advantages of high accuracy at a reasonable cost relative to alternative techniques. Acoustic pyrometry could become of greater interest in the future for 2D temperature profiling, if the price becomes more competitive with other techniques. TDLAS for temperature measurement is of interest, when gas analysis is required. Temperature measurements with an oxygen TDLAS can fail at low oxygen concentrations (under about

12 %-m) and high gas temperatures (over 1400 °C). Future work with TDLAS for temperature measurements should focus on using combustion gases as H_2O which always have a high concentration in the furnace.

The furnace combustion gas temperatures are normally not measured, so it therefore can be a large source of error when using process control software like FOCS to control the reheating process. FOCS can use a gas temperature bias which is based on the burner output when the true gas temperature is unavailable. Therefore two options for improving the FOCS temperature predictions are (1) improve the predicted gas bias or (2) use a measured gas temperature. Gas temperature predictions can be improved by curve-fitting measurements of gas temperatures under varying furnace conditions.

Stock temperature data is important in the hot rolling of steel. Emissivity independent IR pyrometers are commercially available with higher accuracy than conventional pyrometers (multiple wavelength spectropyrometers and pyrometers using a laser to detect surface emissivity). Independent tests at AvestaPolarit have shown these instruments to be worth further investigation.

Furnace wall temperatures in steel reheating furnaces can be accurately and inexpensively measured with thermocouples, which is the current practice. Thermocouples age in service, so all thermocouples used for process control should have a regular maintenance and replacement schedule. Type B thermocouples are recommended as a replacement for Type S thermocouples when the temperature can exceed 1480 °C.

10 ACKNOWLEDGEMENT OF COMMITTEE MEMBERS AND FINANCING

Project research was carried out with the following committee members from Jernkontoret´s TO51.

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Financial support for this research was provided by the Swedish National Energy Administration (STEM) through the Swedish Steel Producers Association (Jernkontoret). Technical support was received from the instrument manufacturers and hot rolling mills involved with this project.

The following project funds were provided:

Category	Funding (SEK)
MEFOS	600 000
Industry (payment in kind)	2 100 000
Total funding	2 700 000

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COMBUSTION GAS IR PYROMETER COMPARISON

Manufacturer	Swedish Supplier	IR model	Approx price	Accessories	Accuracy	Readout	Comments
1. Heitronics Wiesbaden, Germany	Roland Gullqvist Pentronic AB Gunnebo www.pentronic.se	A. KT15.69 B. KT19.69	45 -50 000 55- 60 000	Cooling jacket and protective case available	0.7% and ±0.5C	400-2500C at ±0.1C	Good technology and accessories
2. Mikron Oakland, NJ www.mikroninst.com	Hans Canterus TemFlow Control Hässelby 08-890480	A. MOD M90L B. M67S C. M67	70 000 43 800 35 700	A. Portable B.C. Fixed - 5 300kr cooling jacket	1.0% and ±1C ±0.5% or ±1C ±0.5% or ±1C	600-2200C 600-1750C 600-1750C	Good prices
3. Chino Corp Tokyo, Japan www.chino.co.jp	Åke Samuelsson CLC Products Täby 08-920685	IR-BAXH1	25 000 (Detector only)	GBHH -Signal analyser (6700kr) ZBCH housing (25 700)	1.5% (4.3 mu)	500-1300C	Too low max. gas temp.
4. Diamond Power Specialty Co. Lancaster, OH www.diamond-power.com	Karl-Olaf Karlsson Diamond Superior Sollentuna 08-290440	GASTEMP XR	(furnace drawings requested)		±28 C (±50 F) (ca. 1.8%)	300-1540C (575-2800F)	Designed for boilers--difficult to get price quote and low accuracy
5. JNT Technical Services Little Ferry, NJ	-----	Infra-View 1500	58 000 kr ($ 5500) + import fees		1% or max ±17C (±30F)	120-1650C (250-3000F)	No local supplier
6. Land Infrared Dronfield, UK www.landinst.com	Kjell Huzelius Heraeus Electro-Nite AB Lidingö 08-54480650	CD 1	29 250:	O/WJP water cooled housing 5 055: to 10 830: O/JP-air cooled 5 780:	1% at 600-1500C and 3% 400-1800C	400-1800C	

IR PYROMETER SUPPLIERS

1. General reference

1.1. G.R. Peacock made a list of infrared pyrometer sources at:
http://www.temperatures.com/rtvendors.html

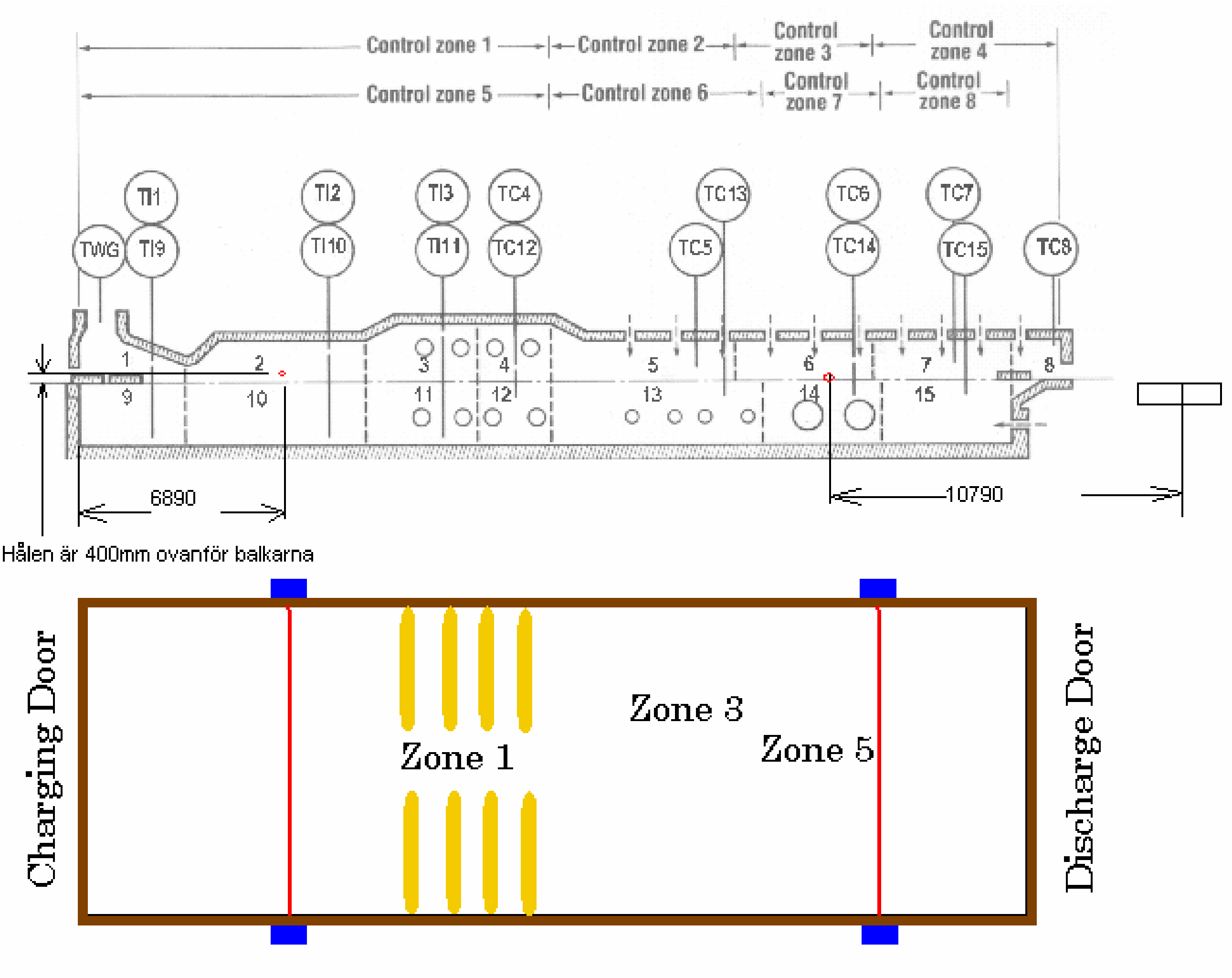
2. Combustion gas temperature pyrometers

1. Heitronics pyrometers: www.heitronics.com
   Sweden: Pentronic: http://www.pentronic.se/eng/frame2.asp
2. Chino: http://www.chino.co.jp/english/main.html
3. Mikron: http://www.mikroninst.com/products/Quantum.htm
4. Diamond Power Specialty Co.: www.diamondpower.com
5. JNT Technical Services: www.infra-view.com
6. Land: http://www.landinst.com/infr/
   Sweden: Heraeus Electro-Nite AB, Furnace thermometer FTS stock temperatures

3. Other pyrometer manufactures, but pyrometers were not for CO2 in combustion gases

1. Omega: http://www.omega.com/temperature/
   Omegas product guide has many low-cost surface temp. pyrometers
2. Exergen: www.exergen.com
   Sweden: Intertechna AB, 054-52 10 00
3. Keller: http://www.keller-msr.de/
4. Raytek: http://www.raytek.com/rod2000/newnareps.htm
   Sweden: Sensotest AB, Järfälla, 08-506 147 90
5. IRCON: http://www.ircon.com/
   Stig Lihagen, Haninge, 08-745 09 73 (Stig said there are no CO2 pyrometers)
6. FAR Assosciates: http://www.pyrometry.com/(Multi-wavelength emissivity correction pyrometer)
7. Williamson Corp: http://www.williamsonir.com/
8. Pyrometer Instrument Co: www.pyrometer.com/(pulsed laser surface emissivity pyrometer)
9. Siemens: 0920-40 55 02 Ardometer pyrometer

The sampling positions in furnace 302 used for TDLAS and CD1 pyrometer trials at SSAB.



A trial to test the effect of the bowl geometry or "reflector" shape of the wall behind wall thermocouples was made at Sandvik (see the minutes of meetings 3 and 4). Various wall shapes behind the thermocouples were tested to see if there was an effect on the temperature readings. The wall shapes were not found to be important, but the penetration depth of the thermocouple was important.