SAF WATER LEAK DETECTION BY THE MEASUREMENT OF GASEOUS WATER VAPOUR

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ABSTRACT

Excessive water ingress through raw materials and failed water cooled components, into a submerged arc furnace (SAF) poses significant difficulties to the efficient and safe operation of the furnace and associated plant. Water ingress from component failures is intense, localised and substantial and results in wet raw materials in the furnace. Very wet raw materials are presented deep into the smelting zone, adversely affecting the process of smelting and increasing the risk of catastrophic failure. These water leaks, often occurring in an enclosed section of the furnace top components, are concealed and can go undetected for significant periods of time. Bridging, agglomeration, and water saturation of raw materials mix, and as a consequence of the above, can go undetected by indirect indicators such as hydrogen concentration in off-gases, raw material feed rate, off-gas temperature, electrode current, electrode resistance or electrode position. Indirect measures such as these usually have a time lag from the actual water leak event. The approaches of water leak detection by water balance or extractive determination are limited in their application due to the high cost, high maintenance and effectiveness of practical application. This solution uses a tuneable diode laser absorption spectrometer to measure water vapour concentration in situ. This instrument uses wavelength modulation spectroscopy to provide a quantitative determination of water vapour in the raw off-gases. The variation of vapour concentration is analysed and used for the detection of water leaks. Engineering considerations include correct placement of instrument in the gas main, use of an appropriately designed inert purge system, thermal protection, data analysis and SPQC techniques, and an experimental approach aimed at balancing absorption, detection time, sensitivity and temperature. The solution is able to detect reasonable water ingress from failed components into the furnace in a short period of time.

1 INTRODUCTION

TEMCO uses four submerged arc electric furnaces in the production of manganese ferroalloys. Water cooled components are an essential requirement for the furnace tops as well as the electrode columns, as these are constantly exposed to furnace offgas, often reaching extremely high temperatures.

Water cooled components are used on most submerged arc furnaces (SAF) and include furnace top components, filler sections, electrode contact clamps, copper flexibles, and cooling water pipes. Failure of these components can result in large volumes of water entering the furnace and adversely affecting the presentation of raw material charge to the smelting zone. Often water leaks occur in enclosed sections of the furnace top or are obscured from sight and the leak goes undetected for a significant period of time. The resulting mix bridging, charge agglomeration, and water saturation pose a significant risk to the safe and effective operation of the plant. Indirect indicators such as offgas hydrogen peaks and raw materials consumption rate can fail to detect the water leak or lag the actual event by long periods of time. Catastrophic events as a result of water leaks are a major contributor to significant injury and fatalities across the ferroalloys industry and necessitate the early detection of water leaks.

Traditional approaches to water leak detection, such as cooling water balances, which uses flow meters, are limited in their application due to the high cost, low sensitivity and practical application in the normal operation of an industrial plant. An alternative detection mechanism is the quantitative determination of water vapour within a given temperature and pressure range by use of wavelength modulation spectroscopy. This technique measures the absorption of EM radiation in the spectral range of the characteristic absorption lines for the target gas, which in the case of water leaks is water vapour.

2 TRADITIONAL SECONDARY INDICATORS

Secondary process indicators have traditionally been used by TEMCO for the indirect detection of water leaks. Unlike direct primary measurements, the secondary indicators have low sensitivity, can have a first order time lag of hours and multiple process dependencies. They are however, well understood by TEMCO and are an important component in furnace top management and water leaks.

Hydrogen concentration in the offgas can be an indicator of water leaks as it is produced when H_20 reacts with CO and C at temperatures above 500 °C. If the water leak is sufficient in volume and is located near one of the 3 electrode, then the water penetrates the raw charge and reacts in high temperature zones. On release the hydrogen gas becomes a constituent of the offgas and is measured in the gas cleaning stage. Hydrogen is not a good indicator of water leaks in areas away from electrodes or during periods of low heat loading because of lower temperatures and lower conversion rates. Under these conditions, time lags can be in the range of minutes to hours and depend on the location of the water leak.[1] For water leak detection, H_2 trends are interpreted and cross referenced with average H_2 concentration from captive water in carbon sources, non-captive water as free or chemical water, offgas temperature, electrode penetration and electrode tip position.

The average energy consumed per batch of raw material charge fed to the furnace (MWHrs per batch) is an indirect measure of consumption rate of raw materials feed to the furnace. Measurements for furnace feed rate, electrode feed rate, furnace bin feed rate as well as an individual batch count are used in the determination of water leaks. Feed rates can be used to indicate water leaks by detecting a reduction in the average number of batches per unit energy over time. Due to the variable nature of energy consumption and feed rates in a SAF process, the feed rates are calculated on a 24hr rolling average basis and therefore have a time lag of 6 to 12 hours. [1]

Furnace pressure trips are another indicator used for the detection of water leaks. Generation of gaseous water vapour and hydrogen, as a result of the water leak, increase the gas volume and pressure in the freeboard and take the furnace outside the operating limits, resulting in a pressure trip. When combined with mix bridging and clinker accumulation the frequency, scale and duration of pressure excursions can be an indicator of longer term water accumulation.

Non characteristic electrode movement patterns can also indicate water leaks because of the changes in conductivity of the materials under and around the electrode due to water. Water ingress into the smelting zone and furnace charge increase the electrical resistance of the furnace and result in deeper electrode positions when controlled on secondary resistance. Unexpected divergence from the typical electrode holder pattern is the process indicator used in this method.

The final two secondary indicators useful in the detection of water leaks are variations of furnace offgas temperature and visual indicators such as steam, cool zones and clinker.

3 MEASUREMENT SYSTEM

3.1 Principle of Operation

The principle of operation of the water leak detection system (WLDS) is that water present in raw materials charge is converted to vapour by hot furnace gas. In the same way as hydrogen it combines with furnace offgas, is heated to gas temperature and is extracted into the gas cleaning and scrubbing equipment. A tuneable laser diode spectrometer is mounted across the gas stream and measures gas concentration. Characteristic sampling is achieved by non-intrusive interaction with the gas, dust or any other composite materials transported in the gas. Changes in pressure, temperature, flow or suspended material density, which impact on water concentration, are avoided. Water vapour is produced over the entire cross section of the furnace and unlike secondary indicators, is able to be measured. A determination of base moisture is made and is established as the process vapour baseline. The introduction of new water sources, such as water leaks, can be detected as a deviation from the moisture baseline. Data analysis of the measurements using time domain statistical process control tools provides a real time technique for the determination of moisture deviations. The statistical analysis provides a mechanism for determining the volume of the new water source and its effects over time.

3.2 TDLAS

"*Tunable Diode Laser Absorption Spectroscopy instruments rely on well-known spectroscopic principles and sensitive detection techniques, coupled with advanced diode lasers and optical fibers developed by the telecommunications industry. The principles are straightforward: Gas molecules absorb energy at specific wavelengths in the electromagnetic spectrum. At wavelengths slightly different than these absorption lines, there is essentially no absorption. By transmitting a beam of light through a gas mixture sample containing a (usually trace) quantity of the target gas, and tuning the beam's wavelength to one of the target gas's absorption lines, and accurately measuring the absorption of that beam, one can deduce the concentration of target gas molecules integrated over the beam's path length*"[2]. It is a specific gas sensing technique used for a wide range of applications including industrial process control. The technique offers high sensitivity, is highly specific and operates at high speed and is well suited to optically noisy processes such as SAF offgas measurements[3][4]. It has been used for high speed flow testing applications and has a design that makes it applicable for industrial applications[5]. Where gas conditions along the path length are uniform at the time of sampling, TDLAS is well suited to high speed flow applications. It is therefore appropriate for use in the determination of gas concentration in industrial gasses such as SAF offgas [2].

"*The WLDS measures the gas concentration by using infrared line absorption spectroscopy. If the absorption of a gas mixture is plotted versus the wavelength, absorption only takes place at certain wavelengths in the spectral region. To perform line absorption spectroscopy, the system uses a diode laser as light source since its spectral width is much narrower than the width of the absorption line. The wavelength of the laser can be selected to be near one absorption line of the gas to be measured. By varying the electric current and laser temperature the laser wavelength is tuned to cover the required narrow spectral range which includes the absorption line. When tuning the laser light over the absorption line it is partially absorbed. From the received laser signal the area beneath the absorption line can be extracted, which is a measure of the gas concentration.*" [2]

The TDLAS instrument uses wavelength modulation spectroscopy, which is the process whereby a characteristic gas is detected by measuring the absorption of light at a frequency specific to the target gas in a similar manner to classic absorption spectroscopy. In the case of wavelength modulation (WM) the absorption band is detected by modulating the frequency of a laser diode at a frequency that is smaller than the half width of the absorption peak. By using the second or fourth harmonic of the characteristic absorption line the detection frequencies are higher than the fundamental frequency. In most industrial processes, noise sources such as flame flicker and dust attenuation are 1/f noise, so the harmonic frequency shift increases the signal to noise ratio thereby increasing the overall noise immunity of the system[3][4]. Kluczynski and Axner [4] outline the theoretical basis of the wavelength modulation spectrometry used in TDLAS. Recently TDLAS has been proposed for the detection of water vapour in the Martian atmosphere, and shown as a viable technique for this type of application.[7]

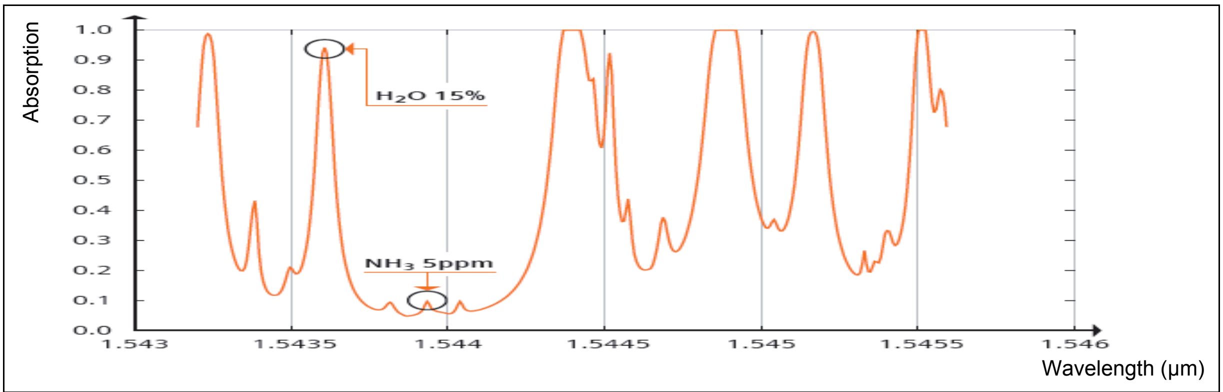

Figure 1: Laser Absorption Spectra (Extract from Siemens LDS6 Instruction Manual)

3.3 Measurement Constraints

The TDLAS instrument must be capable of operating under the physical constraints of furnace offgas system. During smelting, the heating of raw material charge produces high levels of tar and pitch, dust and water vapour. The mechanical design of the system must take into account the contamination and fouling of the optical components, particularly from combination of tar, dust and water vapour. The instrument must also operate in combustible levels of CO and H_2 with gas at temperatures ranging up to 800 °C. The largest constraint of the system is the opacity of the process gas over the wide range of SAF conditions.

A duct mounted instrument must be capable of withstanding radiant heat from the gas duct, be sufficiently industrialized to operate in a heavy industry smelting plant and have at a minimum the same maintenance service interval as the gas scrubber system it is attached to. Unlike secondary indicators, the measurement of a water concentration is a primary process indicator that can be used to detect water leaks as a deviation from the basal moisture.

3.4 Physical Design

The WLDS is an in stream system that requires the TDLAS sensing path to be in the process gas stream. The transmitter and receiver are horizontally mounted in the gas duct or in the upper section of the scrubber pre-conditioner. Light from the laser source of the TDLAS instrument, passes along a fixed optical path length (OPL) from transmitter to receiver and is measured to determine absorption rate and therefore water concentration. The path length is constrained by the gas opacity and is set by installing stainless steel purge tubes. Nitrogen is used for a constant low pressure purge gas and as a periodic high pressure blowback system. Figure 2 shows the configuration of the purge system. The mounting and orientation of the duct mounted units and the scrubber mounted units are illustrated in Figure 3 and 4 respectively. Purge tubes are cut at 45 deg to the gas flow to reduce the likelihood of fouling from dust and tar. An earlier implementation of the system unsuccessfully used sensor units mounted "cross-duct" and perpendicular to the gas flow. In this configuration heavier dust and sinter particles accumulated inside the lower purge tube and could not be dislodged by the purge system. Sensors are mounted on 300mm spool flanges, are mechanically protected from radiant heat and are cooled by the nitrogen purge.
Temperature and pressure variation of the process gas act to change the concentration of the gas and broaden the IR absorption line. Temperature and pressure compensation is therefore required in order for the TDLAS to provide accurate measurement[8][9]. This is achieved by temperature and pressure sensors mounted in duct work and electronically interfaced to the instrument. The spectrometer is interfaced to the plant DCS for signal acquisition, processing and process control. Control actions include process trips, SCADA alarms and operation messaging.

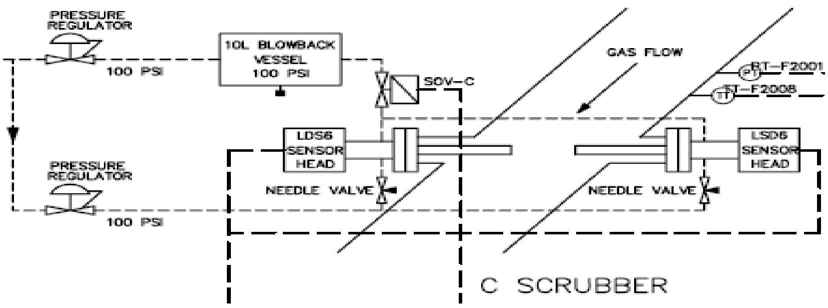

Figure 2: TEMCO F2 Moisture Detection P&ID

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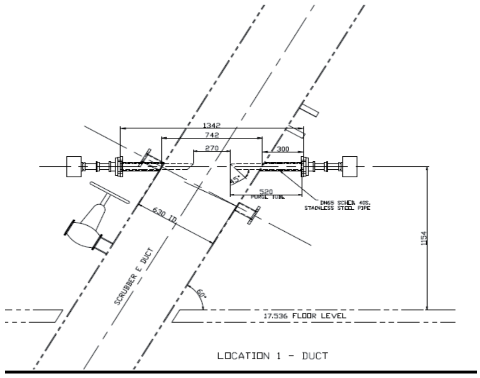

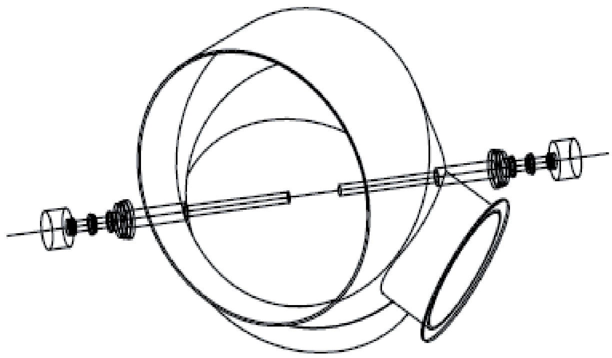

Figure 3: TEMCO F1 E Scrubber LDS Mounting **Figure 4:** TEMCO F3 B Scrubber LDS Mounting

A duct mounted instrument must be capable of withstanding radiant heat from the gas duct, be sufficiently industrialized to operate in a heavy industry smelting plant and have at a minimum the same maintenance service interval as the gas scrubber system it is attached to. Unlike secondary indicators, the measurement of a water concentration is a primary process indicator that can be used to detect water leaks as a deviation from the basal moisture.

4 Results

Several configurations of the TDLAS sensors were trialed over a 12 month period before the system was able to reliably measure water vapour concentration. In the final design the sensors were mounted in the offgas system at a position nearest to the first treatment stage of the wet scrubber. Due to the size of the gas duct, the nature of the offgas and the density of opaque particles in the gas, the Optical Path Length (OPL) was well below the manufacturers recommended OPL of 1000mm. With an OPL in the range of 170mm to 300 mm the resolution of the instrument was impacted by an order of 10. The system is purged on an hourly basis and is configured for a sampling period of 20 seconds. After a trial period of 12 months the system has demonstrated very low maintenance overheads, with a cleaning cycle of more than 6 months.

At times, furnace gas reaches a much higher level of opacity and the laser source is compromised However, these events occur less than 1% of normal operating time and have a duration in the order of minutes. The system has a detection resolution of 1 - 2%. Figure 5 shows the measurements of 8 hour average basal moisture over a 12 month time frame and shows seasonal variation of basal water.

Table 1: Mean Moisture Level deviation of water leak events

Event	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Severity	1	1	1	2	2	2	3	3	4
Mean Difference	2.79	3.50	2.13	3.13	3.10	4.09	3.65	3.96	5.59
Std.Dev Difference	-0.44	-0.77	0.28	0.13	-0.13	0.56	0.11	-1.27	0.61
Variance Difference	-1.91	-2.36	1.44	0.58	-0.57	2.05	0.41	-7.66	2.81
Standard Error	1.00	0.41	0.42	0.35	0.16	0.25	0.37	0.19	0.53
Event	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Severity	4	4	4.25	4.25	4.5	4.5	5	5	5
Mean Difference	4.41	4.40	5.85	5.98	7.89	7.02	14.25	12.79	13.77
Std.Dev Difference	-0.52	-0.31	-0.34	2.65	1.67	1.29	5.87	5.09	0.08
Variance Difference	-2.62	-1.22	-1.48	21.55	9.74	5.48	27.46	70.91	0.15
Standard Error	0.53	0.51	0.43	1.92	1.00	0.59	0.76	1.92	0.11

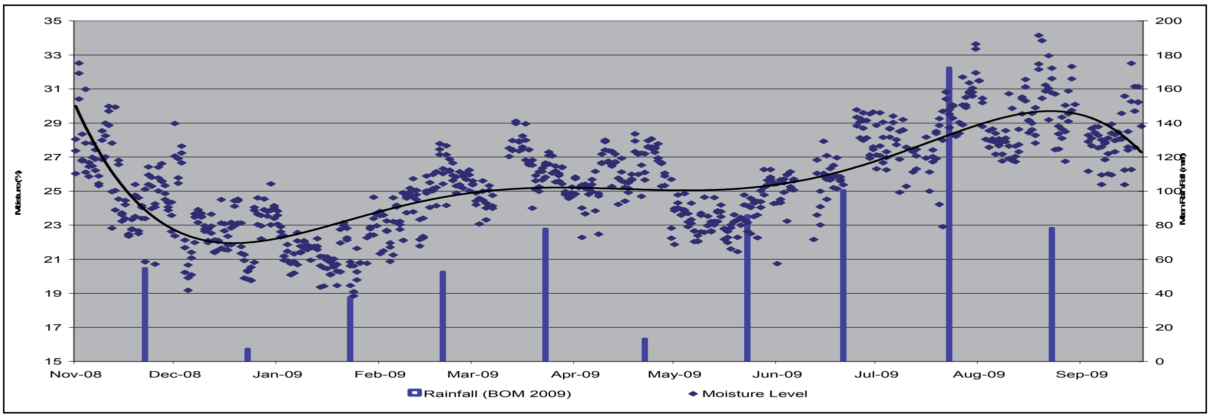

Figure 5: 12 Month Base Moisture

The basis for water leak determination is the measurement of a deviation in the statistical mean of moisture readings. Over a 6 month trial period, water leaks were recorded and categorized on a scale of 1 (small leak < 20L/Min) to 5 (large leak > 60L/Min) and their sample mean compared to a period of no less than 6hrs leading up to the leak. These results are shown in Table 1. During this period, water leaks were determined by conventional indicators, visual inspections and furnace repair schedules. Figure 6 plots the mean difference and the water leak severity for the trial period. This data allowed for the configuration of the SPQC tools used to detect water leaks in real time. Figure 6 shows that smaller water leaks result in a mean deviation of 2-3% with an error margin of 0.6%, whilst larger leaks result in a mean deviation of 6-14% with an error margin of 0.9%.

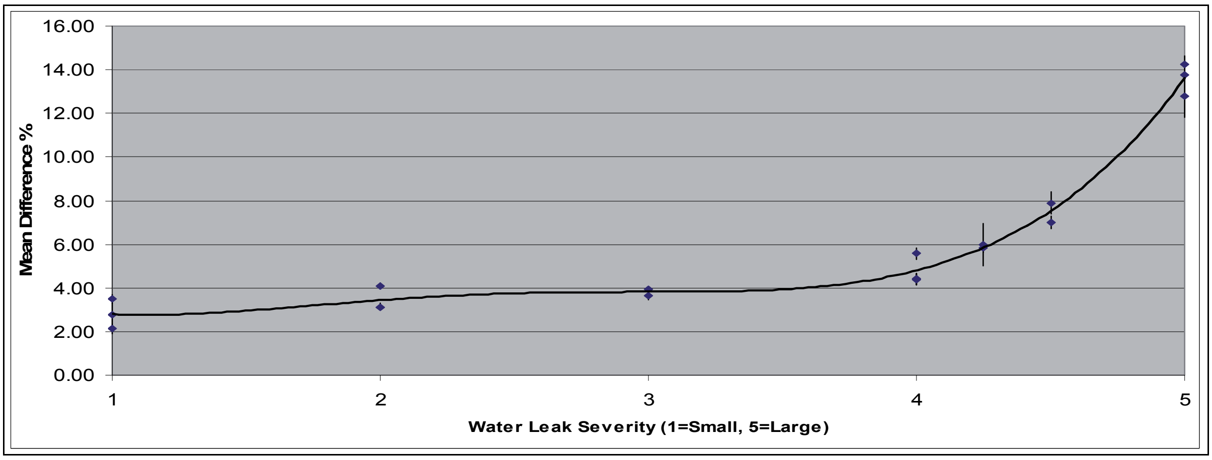

Figure 6: Mean Difference Vs Water Leak Severity

5 SPQC Data Analysis

5.1 SPQC Techniques

Statistical process control was first proposed by Walter Shewart in 1924 for controlling quality of products. A variation on the classic Shewhart control chart that weights recent readings more heavily than less recent readings is the exponentially weighted moving average (EWMA) chart. In practice the EWMA chart is interpreted as a weighted average of all past and the present values [10]. The cumulative sum (CUSUM) chart detects a deviation in process mean by plotting the cumulative sum of all sample points from a specified target [10]. Montgomery [11] advocates the use of EWMA charts and CUSUM charts in industrial processes. EMWA and CUSUM techniques are particularly good at detecting small changes in process mean because unlike Shewart charts they use current and historical process information. EWMA control charts are also robust to non normally distributed data, can be used on individual readings as well as subgroups and auto-correlated data[11].

Mitra [10] outlines some disadvantages of CUSUM's that must be taken into account when using them on real time processes. One of these disadvantages is that whilst CUSUM charts can detect small changes in mean, they can be slow in detecting larger changes in process conditions. Consequently, the WLDS uses a combination of EWMA and CUSUM techniques in performing real time process monitoring. The CUSUM technique used is a one sided CUSUM outlined by Montgomery [11] for industrial processes. For small changes in process mean a CUSUM is employed but only the upper control limit is used in the determination of water leaks. Minitab and NWA Quality Analyst have been used to perform SPQC analysis of offline data.

5.2 SPQC Implementation

The EWMA algorithm implemented is required to account for changes in basal moisture due to seasonal changes in raw materials moisture. Rather than implement an EWMA with fixed targets and control limits, the algorithm adopted is similar to the moving-centre EWMA control chart advocated by Montgomery [11]. The intent of this style of EWMA is to alarm the furnace operator of a large shift in process mean and provide a run chart for process monitoring. EWMA is performed as a 10 minute average of process moisture with UCL set at 7 day average moisture + static margin of 4.5 and a second UCL set at 7 day average moisture + static margin of 5.0.

Being sensitive to small changes in process mean the CUSUM algorithm implemented must also compensate for shorter term changes due to daily rainfall, material recipe variations, and smelting conditions like electrode movements and gas temperature variation. The intent of the TEMCO CUSUM algorithm is to detect smaller leaks, alert the operator and invoke a safety shutdown of the furnace. The target is set to the 6 hour average moisture (+ allowable margin), and the control limit is set to the minimum cumulative deviation that represents the smallest detectable water leak. The CUSUM is reset to zero when the instantaneous process mean drops below the target value. In this configuration the CUSUM targets a medium term mean deviation what allows for a nominal deviation tolerance and a margin of error. The CUSUM is calculated by totalizing the difference in the instantaneous process value and a running 6hr average. A nominal deviation tolerance is determined for each furnace and is in the range of 3 to 5 %. This value constitutes the sensitivity to normal short term changes in process mean due to furnace activity. The error margin is a dynamic value that is in the range of 3-5% and is designed to account for predicted abnormal conditions that may increase the moisture level. This margin is used to desensitize the CUSUM during furnace tapping when the furnace moisture is known to increase by 3-4% for the duration of the tap. The CUSUM is reset to 0, when the instantaneous process value drops below the CUSUM process target. The control limit is set at 10%.

In practical terms the CUSUM can be interpreted as the total volume of water vapour in excess of the volume of water predicted by the 6hr average + a margin. The volume calculation begins when the instantaneous process value exceeds the 6 hour target and is reset on dropping below the target. This technique allows the moisture level to exceed the target for short periods of time without causing a process trip, but still providing detection capabilities for water leaks that result in a process shift outside the normal noise of the smelting process.

A additional moisture alert is also established for a process value that exceed 45% for more than 2 minutes and a process value rate of change of 0.7 per minute that is sustained for more than 4 minutes. This alert provides an additional level of monitoring for very large water leaks that generate large amounts of vapour in a very short time period. The SPQC algorithms outlined have been implemented in real time in the plant control system and generate operator alerts, alarms and plant trips.

Figure 7 and 8 show EWMA and CUSUM process charts for a small water leak (Severity 2) that first alarmed at Sample 96 (2:25AM). The EWMA chart shows that the water ingress most likely occurred around Sample 78 (1:20 AM). The response time of the system in this case was 65 minutes. The CUSUM chart registers the event as out of control at Sample 91 (2:08 AM) and has a response time of 48 minutes. This trace also shows an out of control event at sample 65 (0:56 AM) and suggests that the water leak make have occurred at this time.
Figure 8 and 9 show charts for a much larger leak. The trace shows that the EWMA process value exceeded the static control limit (UCL) within 18 minutes (sample 19) of the leak developing (sample 13). The same trace exceeds the dynamic control limit outlined above (UWL, sample 16) within 6 minutes.

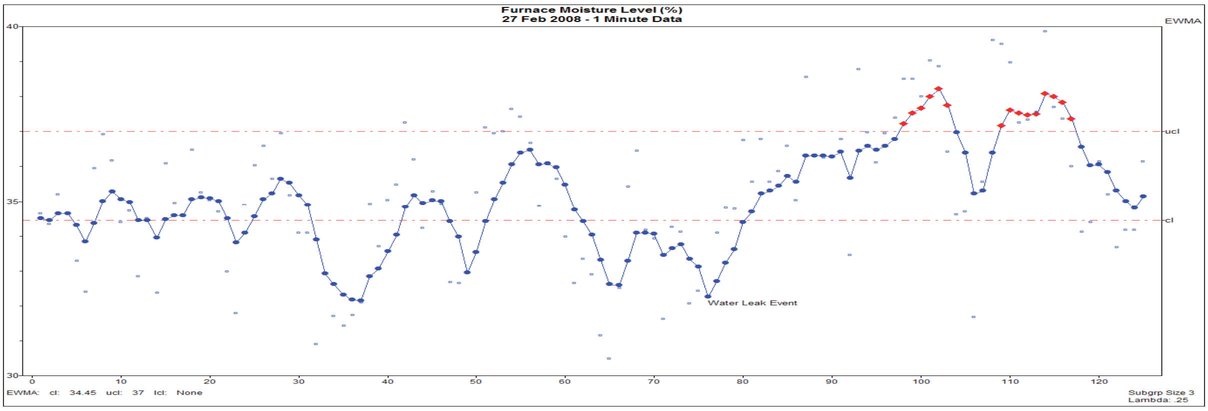

Figure 7: EWMA – Severity 2 Water Leak (20L/Min)

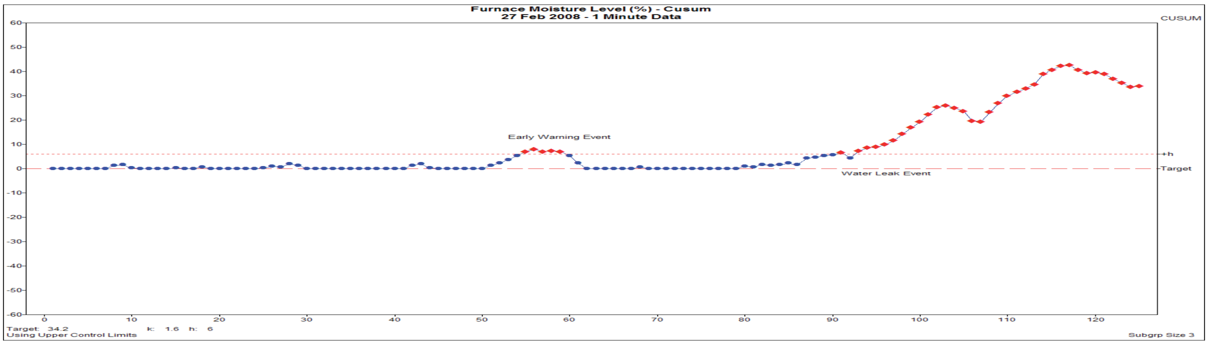

Figure 8: CUSUM – Severity 2 Water Leak (20L/Min)

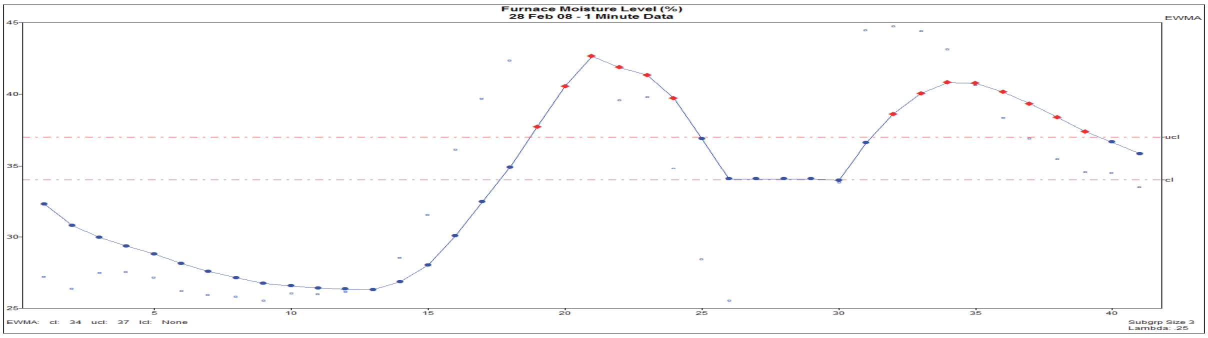

Figure 9: EWMA – Severity 5 Water Leak (70L/Min)

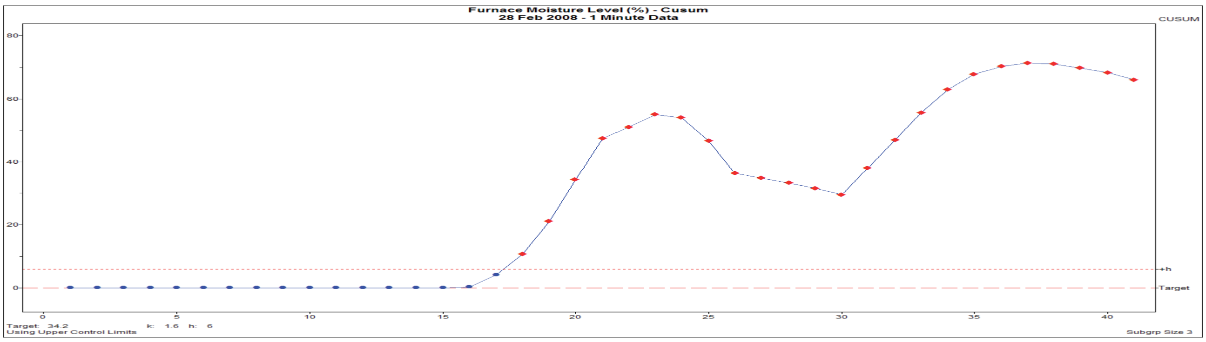

Figure 10: CUSUM – Severity 5 Water Leak (70L/Min)

Table 2: Furnace 1 Water Leak Detection Performance Feb 08 – Sept 08

Month	# Total leak events[1]	# In furnace leak events[2]	# WLDS Leaks Detected[3]	Severity	Details - Location
Feb	5	5	5	1,2,5	Filler sections, Mantle hoses, contact clamps
Mar	2	1	1	2	
April	6	5	5	1,2,5	Electrode flexible, furnace cover, hoses
May	6	3	3	2,3	Electrode flexible
June	2	2	2	3	Electrode flexible, radial beams
July	5	5	5	3	Electrode flexible
Aug	11	9	9	1 - 5	Cooling Pipes, radial beams, furnace covers, filler sections
Sept	4	4	4	2,3	Contact clamps, filler sections

Notes:
1 - # total leak events – All water leaks of furnace. Includes leaks that did not result in water ingress into furnace
2 - # In furnace leak events – water leak events that resulted in water ingress into the furnace
3 - # WLDS leaks detected – Total no of leaks detected by WLDS.

Using the SPQC techniques outlined, the WDLS successfully detected 100% of water leaks that resulted in water ingress into the furnace during the trial period. The measurement system has been installed on all closed and open top furnace's at TEMCO and has produced excellent results. Table 2 outlines the performance of the system on one furnace.

6 SAF Application

The WLDS is applicable for use in SAF environments but must be implemented within the context of sound process understanding, experimental design and scientific process. TDLAS instrument's are based on IR absorption, so it is important to ensure the system meets the requirements:

- Process gas temperature.
- Gas opacity
- Instrument maintenance interval
- Instrument purging

TDLAS provides a superior detection system than traditional extractive gas analyzer systems because it is a non contact and instream. Unlike flow meters used in water balance approaches, the TDLAS equipment is effectively maintenance free, does not need calibration and measures water vapour from all water sources in the furnace. The water balance approach using high precision flow meters has been rejected as a suitable alternative at TEMCO because of the impact of poor water quality, suspended solids and maintainability of a large amount of instruments required. Cooling water circuits at TEMCO can be non-captive when extraneous cooling circuits are added to the system.

Installation of a TDLAS based system on a SAF requires the following processes:

- Install TDLAS instrument with focus on horizontal mounting and the minimization of contamination by good mechanical design and purging. The design should also cater for suitable heat protection and mechanical support for duct mounting
- Establish operating parameters that provide a reliable measurement at a sample interval of more than twice the interval required for operation. An experimental methodology can determine appropriate values for laser amplification, purge tube length, purge gas pressure / volume, high pressure purge period, TDLAS transmission threshold and TDLAS sample time.

- Establish a process data baseline and analyse it in the context of the host process. Determine the normal instrumentation characteristics such as resolution, sensitivity, accuracy and repeatability.
- Introduce a known water source under controlled conditions or conduct operational trials on a production furnace to determine the process value variations that occur for particular water leak events.
- Establish SPQC technique's for the analysis of process data and establishing control limits for detection
- Conduct experimental trials to determine the effectiveness of the system implemented and improve where required
- Commission the system into the DCS and associated plant control systems as well as maintenance and operation systems.

7 CONCLUSIONS

TDLAS technology has been be successfully implemented in an industrial environment on a complex multi-component gas with high levels of dust, tar and water residuals. When used for water leak detection the system is able to measure mean shift of water vapour for the smallest water leak. Experimental process has established the detection range and statistical tools required for data analysis and triggering a water leak event in real time. The system has now been implemented on all four TEMCO furnace's and is used a primary indicator for water leaks.

Ferroalloy smelting involves many complex processes and their interrelationships with water vapour are not well understood. Process data has show that moisture levels are dynamic and are impacted by furnace load, electrode movement, chemical interaction with offgas, temperature, furnace tapping, material changes, and seasonal rainfall. Ongoing research and analysis is focusing on understanding these relationships and refining the process control systems to cater for variance.

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