Simultaneous Inner and Outer Thermography of Rotary Kilns for Hazardous Waste Incineration – Controlled Protective Slagging Results in a Considerable Prolongation of Refractory Life

Kurzfassung

Simultane innere und äußere Thermographie an Drehrohröfen von Sonderabfall-Verbrennungsanlagen – Kontrolliertes Pelzen verlängert die Ofenstandzeit erheblich

Drehrohröfen von Sonderabfall-Verbrennungsanlagen (SVA) werden mit Al_2O_3-reichen feuerfesten Steinen ausgemauert (250 mm bis 300 mm ursprüngliche Steindicke), um den tragenden äußeren Stahlmantel vor den hohen Ofen-Innentemperaturen zu schützen. Die kostenintensive Ausmauerung (rund 300 000 €) sollte ihrerseits gegen rapiden Verschleiß geschützt werden. Jeder direkte Kontakt von schmelzflüssiger Schlacke mit der Steinoberfläche fördert den Steinverschleiß. Im Fall „verschlackender Hochtemperatur-Verbrennung“ mit Austrag schmelzflüssiger Schlacke wird die Ofenausmauerung jedoch – im Prinzip – nicht stärker gefährdet als im Fall „veraschender Niedertemperatur-Verbrennung“ mit Trockentaschung, ganz im Gegenteil, sofern nur der Drehrohrofen im richtigen Temperaturbereich zwischen „zu heiß“ und „zu kalt“ betrieben wird: Die Innentemperatur muss einerseits hoch genug sein, um die Asche überhaupt aufzuschmelzen, sie sollte andererseits aber niedrig genug bleiben, um einen – auf die Steinoberfläche aufziehenden und an ihr anfrierenden – Schlackepelz aufrecht zu erhalten. Aufziehen der Schlacke und Erstarren zum schützenden Pelz beruhen auf dem radialen Wärmeabtransport durch die „mehrschichtige Drehrohrwand“. Nur im Fall „verschlackender Hochtemperatur-Verbrennung“ wird es überhaupt möglich, einen solchen Pelz zu erzeugen und überall dauerhaft aufrecht zu erhalten. Gelingt dies, so verlängert sich die Lebensdauer der Ausmauerung (Ofenstandzeit) sehr beachtlich.

Zur Verbesserung der Pelzbildung werden in einigen Anlagen seit geraumer Zeit Schlackebildner zugesetzt, während in anderen Anlagen dies nur getestet und dann – wegen unbefriedigender Ergebnisse und wiederkehrender betrieblicher Schwierigkeiten – eingestellt wurde, so z. B. im Jahr 1970 bei der BAYER AG. Die Schwierigkeiten lassen sich aber überwinden. Eine erhebliche Verlängerung der Ofenstandzeit wird erzielbar, wenn man den „Pelzungs-Zustand des Ofens“ fortlaufend präzise kontrollieren kann. Die „simultane innere und äußere Thermografie“, wie sie von den Autoren bei der BAYER AG – weltweit erstmals – angewendet wurde, ermöglicht ein erfolgreiches „Pelzen“.

Die an der inneren und äußeren Ofenoberfläche thermografisch gemessenen Temperaturen müssen als erstes exakt lokalisiert und einander örtlich zugeordnet werden. Danach wird aus der lokalen Temperaturdifferenz rechnerisch auf die zugehörige „äquivalente Reststeindicke“ (Gesamtdicke von Reststein und Schlackepelz) zurückgeschlossen. Hierzu benötigt man – neben der thermografischen Hardware – eine entsprechende PC-Software. Diese Software „RotaVos“ wurde 1997/98 entwickelt und in die Praxis umgesetzt; sie ist an jeden Drehrohrofen individuell anzupassen. Mittels der Software „RotaVos“ wird die „simultane innere und äußere Thermografie“ zur „berührungslosen Wanddickenmessung“ am laufenden Ofen. Das Verfahren kann auf alle unverkleideten Drehrohröfen ohne externe Wasserkühlung angewendet werden.

Erste Betriebsversuche zur Anwendung der neuen Methode hatten bald Erfolg. Die notwendige thermografische Hardware und die spezielle Software „RotaVos“ wurden deshalb schon in 1998/99 an den beiden benachbarten Drehrohröfen des BAYER-Entsorgungszentrums Leverkusen-Bürrig installiert und seither durch das Ofenpersonal genutzt. Seit mehr als drei Jahren wird im normalen Betrieb bestätigt, dass das „thermografisch kontrollierte Pelzen“ tatsächlich durchführbar und erfolgreich ist. Der Steinverschleiß reduzierte sich von > 200 mm pro Jahr auf < 50 mm pro Jahr. Das „thermografisch kontrollierte Pelzen“ erlaubt demnach Ofenstandzeiten von rund vier Jahren (Verlängerungsfaktor ungefähr zwei bis vier).

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Introduction

The BAYER AG operates at its German sites Leverkusen, Dormagen and Uerdingen four rotary kiln units for hazardous waste incineration. Two of them are located at the BAYER-waste management centre in Leverkusen-Bürrig. The four units have a similar, BAYER-typical design as shown in Figure 1 and are all run in the so-called mode of “slagging combustion”, i.e. at elevated kiln temperatures of 1050 °C (kiln exit) up to 1450 °C in the burner-jet flames or up to 1300 °C at the slag/brick-surface in the hotter middle part of the slowly rotating kiln.

The brick life of the two neighboured kilns in Leverkusen-Bürrig has been different, mainly due to the different waste composition (with

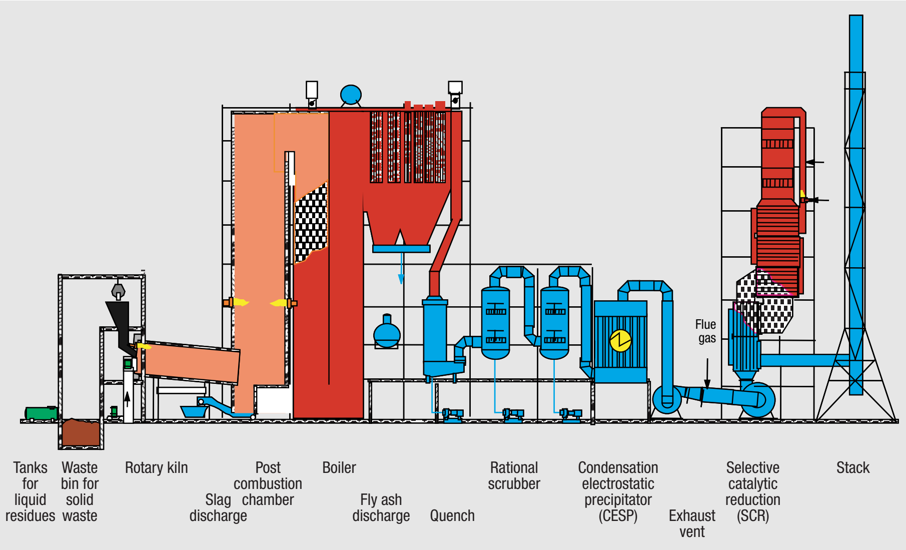

Figure 1. Hazardous waste incineration plant (KILN A) in Leverkusen-Bürrig.

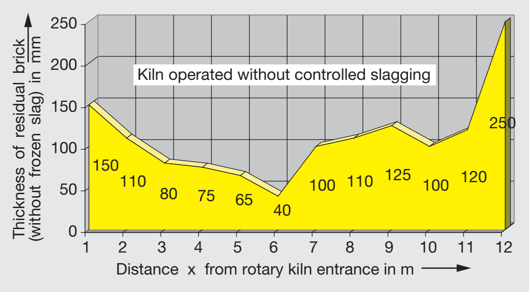

Figure 2. Residual brick thickness of KILN A after only 6000 hours of uncontrolled operation (brick thickness only, measured by direct drilling after final shutdown in November 1997).

and without solid waste) and to the slightly different kiln capacities. The kilns had attained until 1997 a brick life of typically only 6000 to 7000 hours in case of KILN A (combusting liquid, pasty and solid wastes) and 20,000 hours in case of KILN B (combusting only liquid and pasty wastes).

The main reason for this great difference in brick life is the solid waste feed and its often high content of "fixed carbon" [1, 2]. Carbon burn-out promotes reducing combustion conditions at the surface of the devolatized combustion-bed within the kiln. This reduces Fe_2O_3 (dissolved in the slag) to its lower melting form FeO, thus lowering the slag melting temperature considerably.

As brick wear progresses, the brick thickness is diminishing from an original thickness of 250 mm down to 40 to 50 mm as a minimum. Having reached this limit, the refractory lining must be renewed, totally or at least partially.

A typical wear pattern is shown in Figure 2 with the final axial profile of the "residual brick thickness" of KILN A (operated without controlled slagging) in November 1997, after only 6000 hours.

In 1997 a BAYER-development project for "Prolonging Refractory Life" was initiated, aimed at extending the refractory life of both rotary kilns, which were in the meantime both fed with solid waste (unshredded in case of KILN A, shredded in case of KILN B).

Slagging Combustion or Dry (Ashing) Combustion

In case of "slagging combustion" the inner temperatures (approximately 1100 to approximately 1400 °C) are considerably higher than in case of "dry (ashing) combustion" (approximately 800 to approximately 1100 °C). But slagging combustion is not necessarily worse for brick life than dry (ashing) combustion. Under slagging combustion attained refractory life will be even longer than under dry (ashing) combustion, if the kiln-slagging is done properly, for example based on thermographical control as described here. Theoretically, brick wear might be eliminated completely in case of "slagging combustion", if all brick heads and brick joints were permanently covered by a frozen slag layer, see Figure 3, showing still virgin bricks under the frozen slag-layer.

Main points to achieve progress in daily industrial practice:

- The formation and maintaining of a protective frozen slag-layer on top of all brick heads and brick joints necessitates dependable information about the kiln's status (axial and peripheral profiles of the "equivalent brick thickness" as total sum of the thickness of residual brick and frozen slag), monitored online by "simultaneous inner and outer thermography".
- The maximal inner surface temperature, somewhere in the kiln's hotter middle part, must be controlled ("inner thermography") and minimized, for example by shifting the air distribution towards "less primary air/more secondary air". (Outer means of temperature control as water spray cooling or enforced outer air cooling [4] were not applied here.)
- Some basic know-how is needed about the slag's melting-behaviour, as well with respect to its hemispherical melting-temperature and softening-temperature, as with respect to the so-called "width of the lower melting-point interval" (temperature difference between hemispherical melting-point and softening-point).
- Further know-how and operational means must be available to alter the melting behaviour, by adding sand and/or other additives to the kiln feed.
- Last but not least, highly liquefying sodium-rich compounds should be eliminated out of the solid waste feed as far as possible.

"Controlled protective slagging" requires a balanced kiln operation between "too hot and too cold". There are many aspects of a balanced kiln operation. Think for example about the necessary axial slag transport in case of slagging combustion. On the one hand, the inner surface temperatures must be maintained low enough to keep everywhere – directly on top of the refractory – a protective frozen slag-layer. On the other hand, the inner kiln surface temperatures must be maintained high enough to keep – on top of that frozen slag-layer – a sufficiently liquefied, mobile "viscous slag film", slagging the kiln wall constantly under the influence of kiln rotation, and at the same time flowing axially towards the kiln exit.

When a protective frozen slag layer is not achieved anymore, see Figure 4 showing exposed brick heads in the kiln's hotter

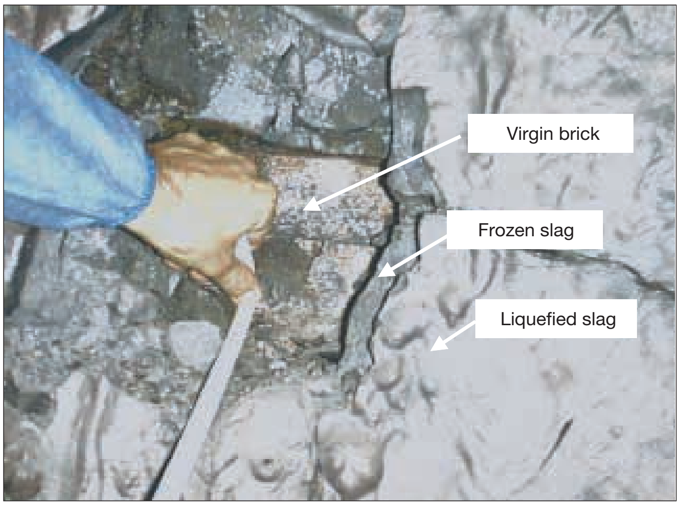

Figure 3. "Virgin bricks" under a protective frozen slag-layer.

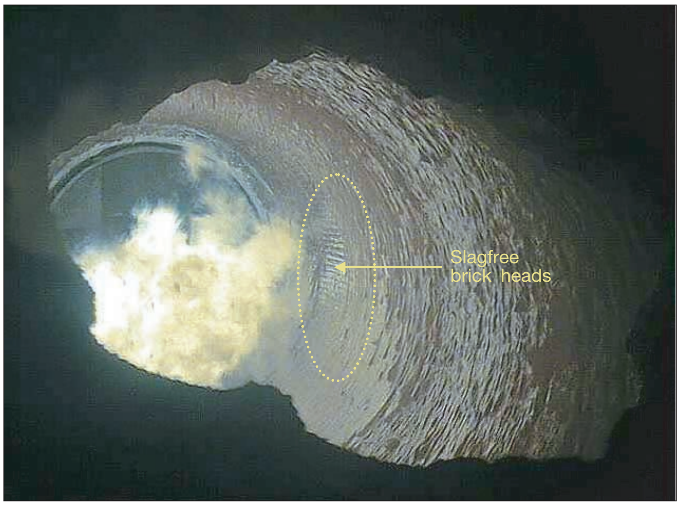

Figure 4. Normal view back into KILN A (first exposed brick heads visible at the right hand side).

middle part (right hand side), the kiln operator must start "slagging" the kiln's wall.

Thermographical Approach

The described combined "simultaneous inner and outer thermography" as a new "non-contact wall thickness measurement" is, as far as is known to us, the first application worldwide in rotary kilns for hazardous waste incineration.

Outer Temperature Measurements

Outer thermographical temperature measurements are common practice in the cement industry, using so-called "line scanners". This well-known measuring technique has been applied – since around 1989 – at some rotary kilns for hazardous waste incineration, too.

Figure 5a shows an outer view at the KILN B (digital photo). As visible, the shell is partially obstructed.

Figure 5b shows the corresponding outer temperature profiles (mean values as well as minimum and maximum values during one kiln rotation) as measured by a thermographical line scanner and evaluated by "RotaVos".

Inner Temperature Measurements

Inner thermographical temperature measurements, using a so-called "firebox camera", are applied in municipal solid waste incinerators for control of the burning zone location on the grates. Thermographical firebox cameras are also applied in other thermal processes (control of cement clinker cooling, of metal melting, of glass melting and glass cooling etc.).

Figure 6a shows a thermographical image (BAYER-infrared-picture), made by the firebox camera M9200, looking backwards – through the post-combustion chamber – into KILN B; the thermocouple element at the kiln exit is visible even in this picture (high dissolution of the tested firebox camera).

The firebox camera must apply "flame filters" to enable a clear view – through the kiln gas – directly at the slag/brick-surface, to measure the temperatures of the inner slag/brick-surface and not of the flame. Therefore, such a camera is working in a narrow wave length range of high "transmissivity of the combustion gases" (away from the CO_2 and H_2O radiation bands). For the same reason of visibility, dust forming wastes should be excluded from the waste feed during control measurements, minimizing gray radiation.

Figure 6b shows three thermografically measured axial profiles of the inner slag surface temperature (along axial lines at the right hand, left hand and upper kiln side) in KILN A, evaluated by "RotaVos". The lower horizontal line is indicating the gas temperature at the kiln exit, the so-called "kiln exit temperature", given by the thermocouple element or measured thermographically along the thermocouple element's outer surface. The thermographical temperature is almost identical (within ± 25 °C) with the thermocouple temperature itself.

The excess-temperature in the kiln's hotter middle part as marked in Figure 6b (200 °C = temperature difference between the maximal inner surface temperature and the

Figure 5a. View at the outer shell of KILN B.

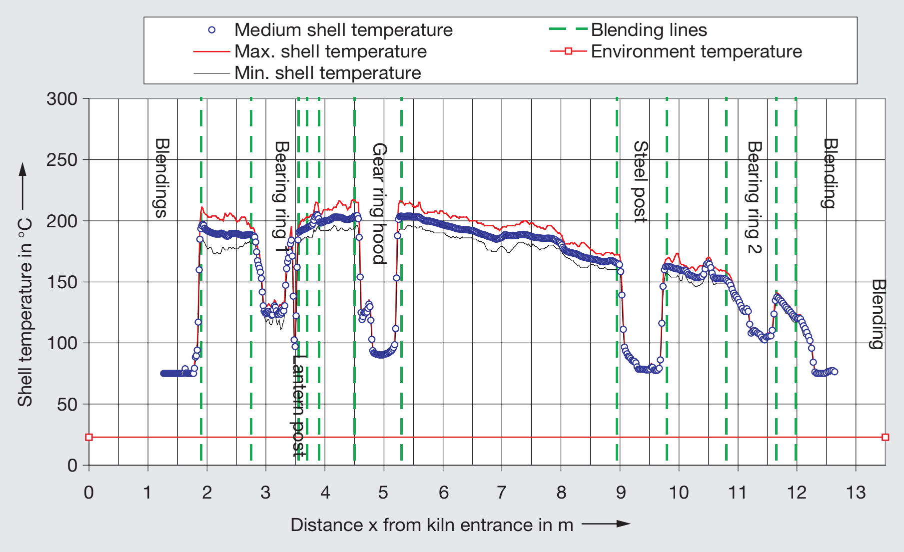

Figure 5b. Outer shell temperatures (mean values as well as minimum and maximum values during one kiln rotation) at KILN B.

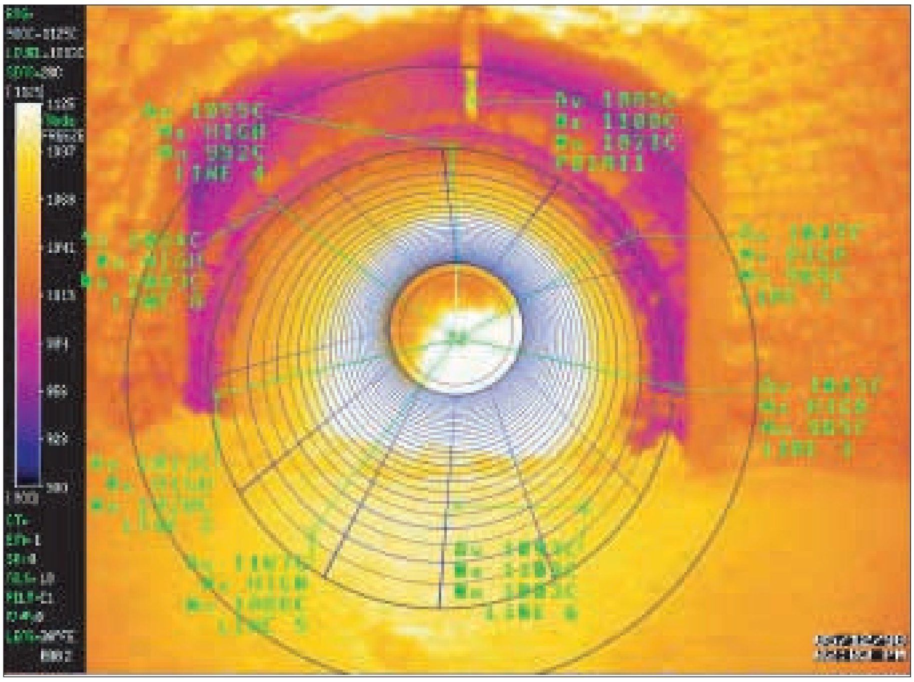

Figure 6a. Thermographical view back into KILN B with a PC-designed "cylindrical wire basket model of the inner kiln" [Vosteen, 1998].

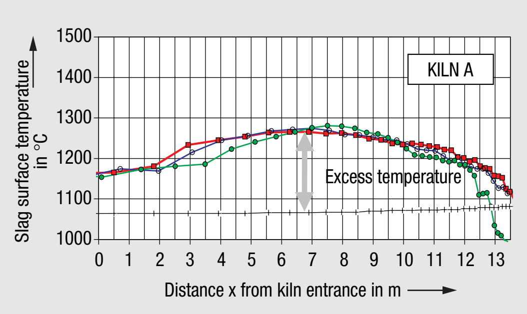

Figure 6b. Inner axial temperature profiles in KILN A along different axial lines (at the right hand, left hand and upper kiln side).

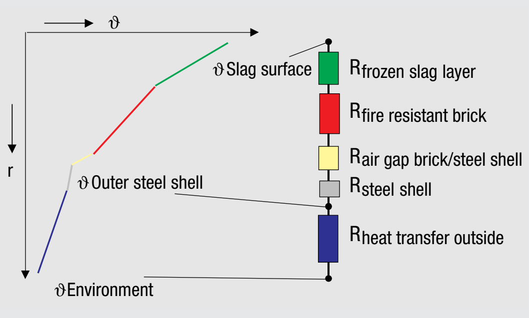

Figure 7. Sketch of the radial temperature profile $\vartheta(r)$ in the kiln wall and of the corresponding heat transport resistances R_i.

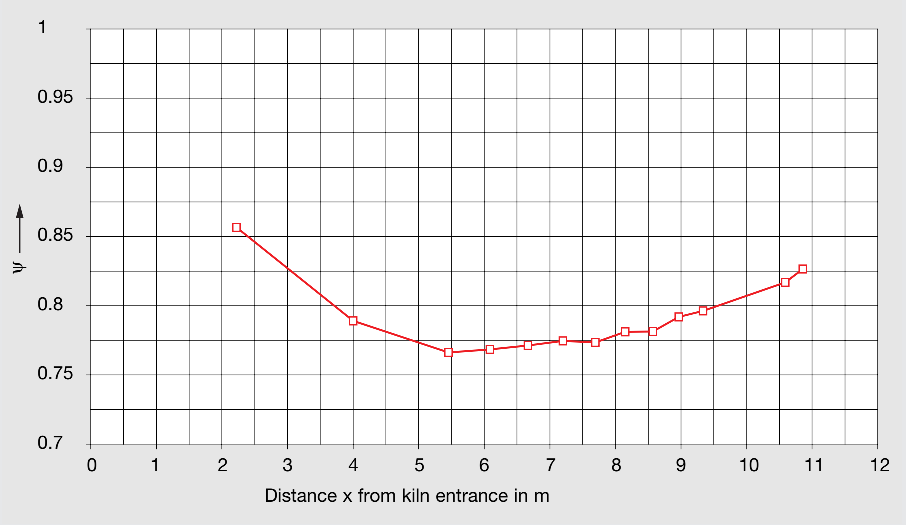

Figure 8. Axial profile of the resistance ratio Ψ (x) in KILN A on August, 20, 1998.

thermocouple temperature), has to be limited with respect to the slag's melting behaviour, as will be discussed later.

Evaluation of the Local Temperature Differences

The evaluation of the local differences between the inner and outer temperatures is based on well-known laws of quasi stationary heat transfer, see Figure 7. The partial temperature difference ($\vartheta_{inner\_slag\_surface} - \vartheta_{outer\_steel\_shell\_surface}$) as well as the total temperature difference ($\vartheta_{inner\_slag\_surface} - \vartheta_{environment}$) stand for the corresponding sums of heat transfer resistances. Therefore the thermographically measured ratio ψ of these two temperature differences

$$\Psi = \frac{\vartheta_{inner\_slag\_surface} - \vartheta_{outer\_steel\_shell\_surface}}{\vartheta_{inner\_slag\_surface} - \vartheta_{environment}} \quad (1)$$

can be interpreted as well as the ratio of the corresponding heat transfer resistances:

$$\Psi = \frac{R_{slag\_layer} + P_{brick} + R_{air\_gap} + R_{steel\_shell}}{R_{slag\_layer} + R_{brick} + R_{air\_gap} + R_{steel\_shell} + R_{outer\_heat\_transfer}} \quad (2)$$

Ψ (x) as a function of the distance x from the kiln entrance gives a qualitative image of the axial wall thickness profile; see Figure 8 as an example of KILN A, demonstrating heightened brick wear in the kiln's hotter middle part, caused there by the highest local heat burden, see excess-temperature in Figure 6b.

1 - Ψ (φ) as a function of the circumferential angle φ (= 0°... 360°) stands for the "open kiln width" in a chosen kiln cross section at x = constant, see Figure 9:

The "elliptical shape" of the kiln's "free cross section" at x = 2.02 m (Figure 9) is easily explained: In 1997 the brick lining had been made up of two different brick qualities – for testing reasons. The diagram shows that the brick quality I (installed right hand side, covering 60 % of the circumference) could not withstand the thermo-mechanical impact there, while the brick quality II (installed left hand side, covering 40 % of the circumference) was more stable. But already at x = 2.75 m both linings do not show significant differences in brick thickness anymore.

The primarily thermographically measured resistance ratio Ψ, as well as the "free kiln- width" 1- Ψ depend on:

- the thickness s_{slag_layer} of the frozen slag-layer and its thermal conductivity λ_{slag_layer}
- the thickness s_{brick} of the residual brick and its thermal conductivity λ_{brick},
- the width s_{air_gap} of an assumed (or in fact existing) air gap between the bricks and the inner steel shell surface and of its "effective thermal conductivity" (including thermal radiation),
- the outer heat transfer coefficient $\alpha_{outside}$.

The thermal conductivities λ_{slag_layer} and λ_{brick} depend on the density (or porosity) and – with minor influence – on the local wall temperatures too. Examination of some slag lumps, removed from the kiln's frozen slag layer (see Figure 3), revealed that the density of frozen slag (2.5 to 2.9 g/cm^3) and the density of refractory bricks are nearly the same. Therefore the thermal conductivities of brick and frozen slag should be the same, see Figure 10.

A requirement for the thermal calculations is the outer heat transfer coefficient (heat transfer from the outer shell to the environment). This heat transfer coefficient may be calculated classically, i. e. based on the known superposition of heat transfer by free convection and by thermal radiation, depending on the local temperature at the outer shell surface, see Figure 11.

A further requirement is the (mean) width of the air gap between brick and inner steel shell. It must be mentioned that the assumed air gap may be a real physical parameter; or it is only an empirical "adaption factor": The air gap width is playing an important role when bringing together exactly the thicknesses, online obtained thermographically, with those thicknesses, measured by slag/brick-drilling after shutdown of the kiln.

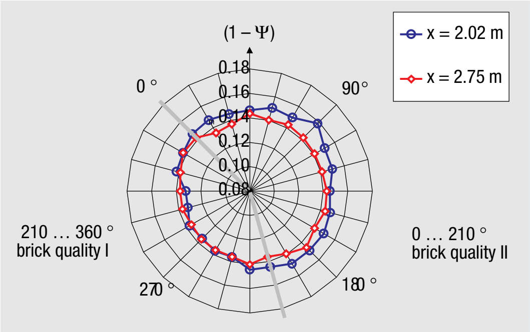

Figure 9. "Free kiln-width" (1 - Ψ) – Peripheral profiles at x = 2.02 m and at x = 2.75 m distance from the entrance of KILN B on May, 28, 1998.

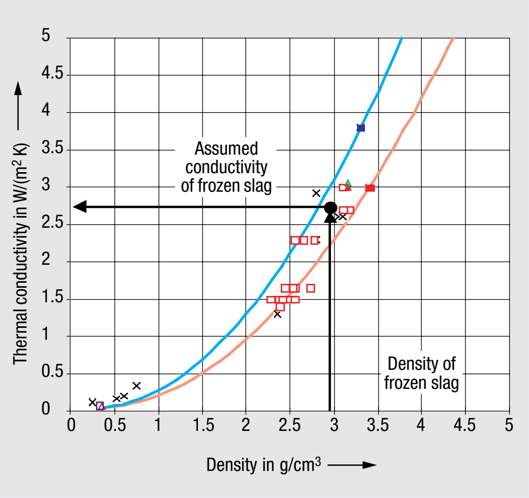

Figure 10. Thermal conductivities of heavy and light refractory bricks at 700 … 800 °C and of air at 750 °C.

Figure 12 shows the axial profile $s_{slag+brick}$ (x) as sum of both slag thickness and brick thickness, the so-called "equivalent brick thickness".

The thermographically obtained profiles of the "equivalent brick thickness" do agree very well – after primary adaptation of the (mean) air gap width – with those profiles, measured directly by drilling.

Drilling must only be done from time to time, when a kiln has to be cooled down for other plant-maintenance reasons. Experience has shown that the air gap width may vary from kiln to kiln, but doesn't change much at the same kiln during its brick life, with the exception of the first months of operation (brick settling).

Melting Behaviour of Ashes and Slags

Within the scope of this paper it is not possible to describe the melting behaviour of coal ashes (approximately 450 data sets) and hazardous waste slags (approximately 40 data sets) in full detail. An extensive report will be given later in a separate publication. Only some reference can be made:

As mentioned above, low melting sodium-rich compounds should be eliminated out of the solid waste feed as far as possible. Under high temperature combustion, sodium-halogenides are rarely found in kiln exit slags, because they are volatized and transferred – via evaporation/sulphatation/desublimation – into the boiler fly ashes. Besides this, the melting behaviours of coal ashes and hazardous waste slags are strongly influenced by

- the slag's iron-content within the slag's component-triplet "$FeO_n – SiO_2 – Al_2O_3$" (well understood as the mass fraction $FeO_n / (FeO_n + SiO_2 + Al_2O_3)$, expressed in weight-% with possible values ≥ 0 to ≤ 100 %) and by
- the "oxidation state" of the iron oxide FeO_n within the slag's multicomponent mixture. Dissolved Fe_2O_3 (pure substance melting point: 1580 °C) may be reduced to FeO (pure substance melting point: 1390 °C), locally depending on the oxidizing or reducing kiln atmosphere.

The diagrams in Figure 13a (oxidizing conditions) and Figure 13b (reducing conditions),

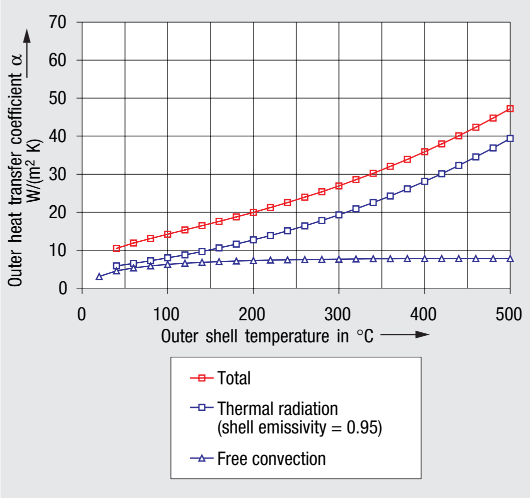

Figure 11. Outer heat transfer coefficient $\alpha_{outside}$ (upper line) by free convection and superimposed thermal radiation (shell emissivity ε = 0.95).

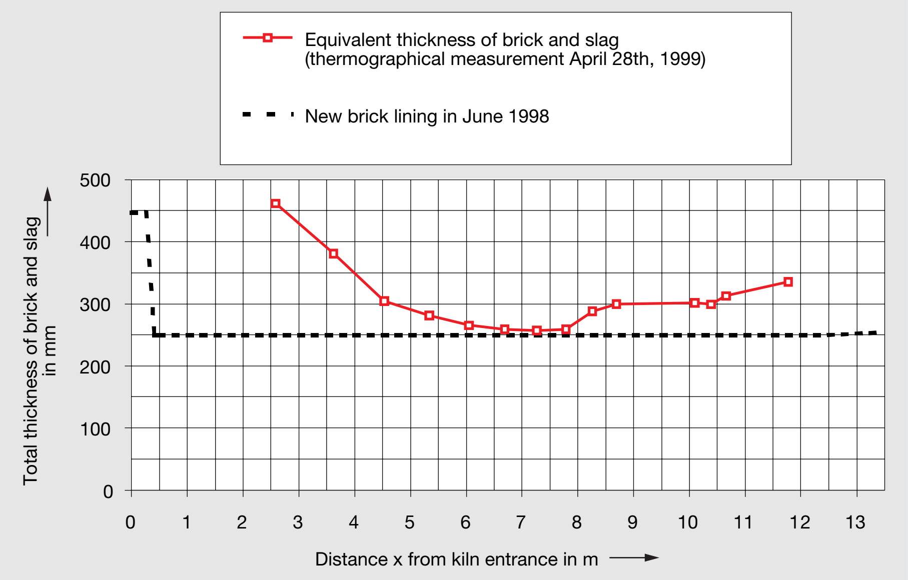

Figure 12. Axial profile of the equivalent brick thickness $s_{slag+brick}$ (x) at KILN B, automatically calculated by „RotaVos" on April, 28, 1999.

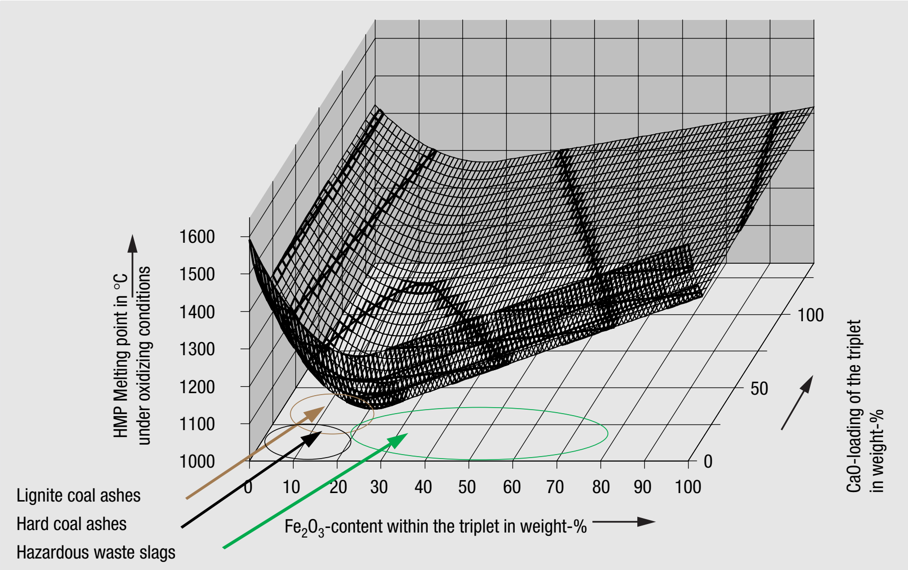

Figure 13a. Melting-point hammock under oxidizing combustion conditions (half-quantitative model, based on some 500 data sets, Vosteen, 1999).

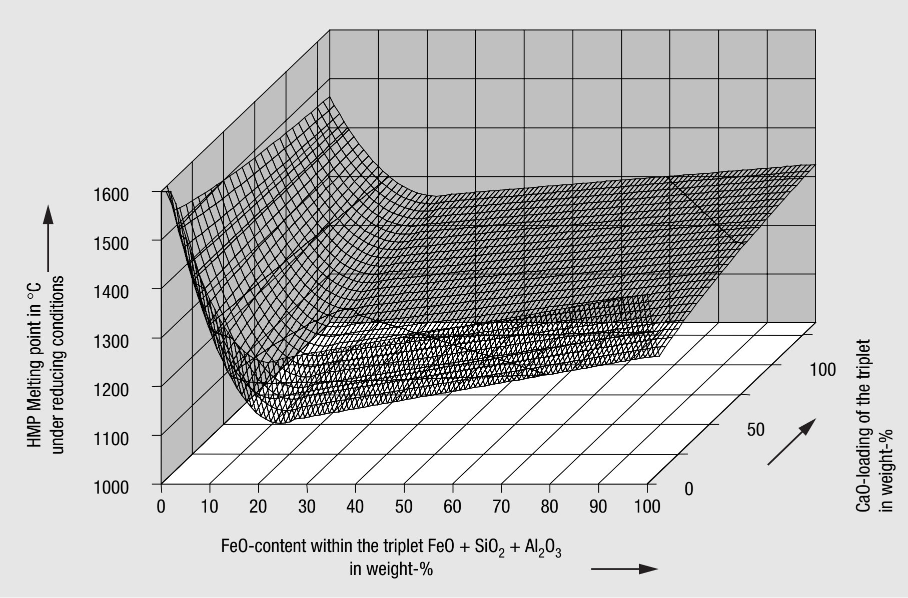

Figure 13b. Melting-point hammock under reducing combustion conditions (half-quantitative model, Vosteen, 1999).

based on the compiled two data sets for coal ashes and slags, provide clarification to the known fact, that a perfect frozen slag-layer is melting away within a few hours, if the local kiln atmosphere (at and in the burning kiln bed) is changed from oxidizing to reducing conditions. This change may happen, when for example activated carbon waste is added to the kiln's feed, causing a reducing atmosphere at/in the combustion bed, and when nothing else is done to compensate for the resulting melting point depression.

Another important aspect concerns the triplet's so-called CaO-loading, i.e. the mass ratio CaO/(FeO_n + Al_2O_3 + SiO_2), and its influence on the slag's "hemispherical melting point" itself, as well as on its "lower melting-point interval", understood as the temperature difference between the slag's hemispherical melting point and its softening point. The "lower melting-point interval" is a "material quality" of the slag's component mixture. An increase of the CaO-loading first lowers the melting point and later heightens it. The kiln's "excess-temperature" (see former Figure 6b), which is dependant on kiln operation, mainly on the air distribution, should not exceed the slag's "lower melting-point interval".

A decisive increase of the CaO-loading by adding lime, as studied in [3] to minimize heavy metal slag-elution, will diminish the "lower melting-point interval" considerably. Any strong increase of the CaO-loading leads to a so-called "short slag", making kiln slagging nearly impossible, because no kiln can

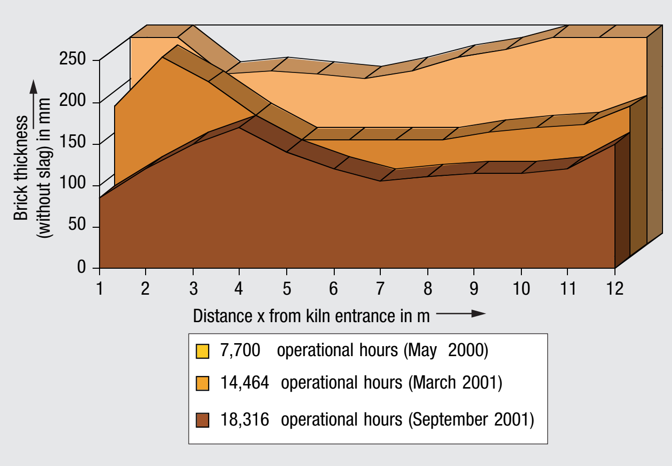

Figure 14a. Three brick thickness profiles of KILN A (bricks only, thickness measured by direct drilling).

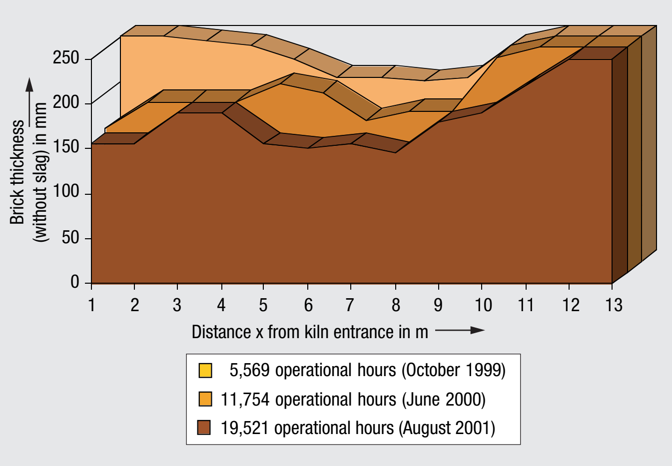

Figure 14b. Three brick thickness profiles of KILN B (bricks only, thickness measured by direct drilling).

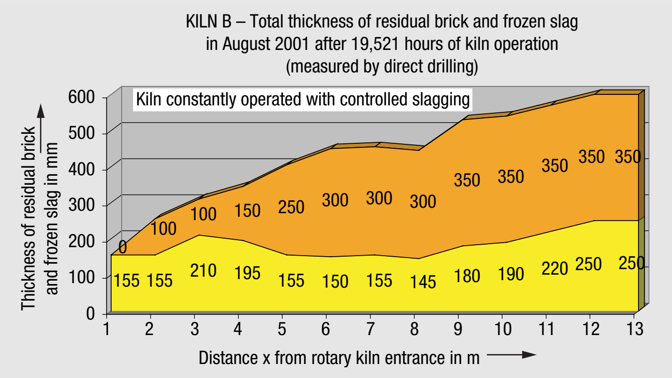

Figure 15a. Heavily slagged KILN B in August 2001 after 19,521 hours of controlled operation (thickness measured by direct drilling).

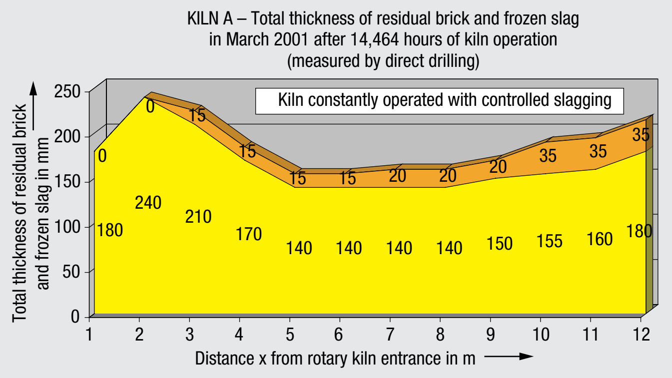

Figure 15b. Decently slagged KILN A in March 2001 after 14,464 hours of controlled operation (thickness measured by direct drilling).

be operated strictly isothermal. Therefore, the slag within the kiln would be either immobile (like “ice”) or highly mobile (like “water”), while “slagging” and “axial slag transport” necessitate both, a mobile slag film on top of an immobile frozen slag-layer.

Industrial Results

By “thermographically controlled slagging”, based on “simultaneous inner and outer thermography”, as described in this paper, the brick life of KILN A (formerly only 6000 to 7000 hours) was considerably increased, see Figure 14a, indicating that the brick life of this kiln – after almost 20,000 operational hours – has not yet come to its end. A new bricklining was installed after 21,776 operational hours in March 2002.

Figure 14b describes the corresponding results at the other KILN B (with formerly some 20,000 hours brick life), indicating that the application of “thermographically controlled slagging will prolong the brick life of this kiln up to possibly some 40,000 hours.

Under actual waste management aspects, the applied method has an additional advantage: A thermographically-controlled kiln can be operated until a minimal residual brick thickness has been reached indeed. This advantage became obvious at the end of 1998, enabling a prolonged operation of KILN A until April 1999, giving five months time for maintenance works at other kilns.

Final remarks: A kiln mustn’t always be slagged as heavily as shown in Figure 15a. But slagging only decently – as shown in Figure 15b – might not be sufficient for brick protection.

Summary and Conclusions

It has been demonstrated that “thermographically-controlled slagging” can be successfully applied to the industrial operation of rotary kiln incinerators and that the developed new method, reducing brick wear to less than 50 mm/year, will prolong brick life considerably to 20,000 h and possibly far more. The applied method enables the plant operations manager to forecast the next required kiln shutdown more exactly, not requiring intermediate kiln shutdowns to verify brick thickness by drilling. The investment for the thermographical hardware has been returned – by reduction of brick wear at two neighboured kilns – within less than six months.

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