CEMENT INTERNATIONAL
▸ PROCESSING ▸ PERFORMANCE ▸ APPLICATION

Reprint from / Sonderdruck aus: Issue No.: 2/2015, pp. 62 – 69

Kiln shell cooling by water evaporation, controlled by infrared temperature measurement

Ofenmantelkühlung durch Wasserverdampfung, geregelt durch Infrarot Temperaturmessung

▸ P. Kalkert, KIMA Echtzeitsysteme GmbH, Jülich, N. Kosetzki, HeidelbergCement AG, Ennigerloh, P. Küllertz, Verein Deutscher Zementwerke (VDZ), Duesseldorf, Germany

Verlag Bau+Technik GmbH · P.O. Box 12 01 10 · 40601 Düsseldorf/Germany · Tel.: +49 (0) 211 / 9 24 99-0

P. Kalkert, KIMA Echtzeitsysteme GmbH, Jülich, N. Kosetzki, HeidelbergCement AG, Ennigerloh, P. Küllertz, Verein Deutscher Zementwerke (VDZ), Duesseldorf, Germany

SUMMARY

The increased demands for noise protection during the operation of rotary kilns close to residential areas and rising energy costs have raised the question as to whether the classical fans used for cooling kiln shells could be replaced by water cooling. Detailed examination of the thermal energy that is dissipated through the surface of the kiln shell during normal operation has shown that comparatively small quantities of water of about 1 l/s are sufficient to cool the entire kiln provided the water is completely evaporated. Flat fan nozzles, which spray a very narrow fan-shaped jet of water onto the rotating kiln, are positioned next to one another in the axial direction to control the application of this quantity of water to the kiln. The flow of water through each nozzle is controlled by an IR pyrometer so that the kiln shell temperature at the location of the nozzle maintains a predetermined target value over the entire circumference. Tests on a kiln have shown that this method does work and is also highly suitable for selective cooling of hot spots and reducing mechanical stresses in the kiln shell. Examination of the effect of the water and of limescale deposits on the hot kiln shell led to the finding that no significant detrimental effects can be expected over a period of one year. Operation of the initial prototypes and production models shows that a substantial reduction in noise emission and power consumption is achieved. Hot spots can be cooled very selectively by precise application of the water, which extends the kiln running time until repairs are carried out.

ZUSAMMENFASSUNG

Gestiegene Anforderungen an den Lärmschutz beim Betrieb von Drehrohröfen in der Nähe von Siedlungen sowie steigende Energiekosten führten zu der Frage, ob die klassischen Gebläse zur Kühlung des Ofenmantels durch eine Wasserkühlung ersetzt werden könnten. Eine detaillierte Betrachtung der thermischen Leistung, die im normalen Betrieb über die Mantelfläche des Ofens abgeführt wird, zeigte, dass vergleichsweise geringe Wassermengen von ca. 1 l/s zur Kühlung eines gesamten Ofens ausreichen, wenn das Wasser dabei vollständig verdampft wird. Um diese Wassermenge kontrolliert auf den Ofen zu bringen, werden in axialer Richtung nebeneinander aufgereihte Fächerdüsen eingesetzt, die einen sehr schmalen „Wasserfächer" auf den drehenden Ofen sprühen. Der Wasserdurchfluss jeder Düse wird jeweils über ein IR-Pyrometer so geregelt, dass die Ofenmanteltemperatur an der Position der Düse über den ganzen Umfang einen vorgegebenen Sollwert einhält. Tests an einem Ofen haben gezeigt, dass das Verfahren funktioniert und sich darüber hinaus sehr gut eignet, um gezielt Hot Spots zu kühlen und mechanische Spannungen im Ofenmantel zu reduzieren. Betrachtungen zum Einfluss des Wassers bzw. von Kalkablagerungen auf den heißen Ofenmantel führten zu der Erkenntnis, dass über einen Zeitraum von einem Jahr keine signifikante Beeinträchtigung zu erwarten ist. Der Betrieb von ersten Prototypen und Seriengeräten zeigt, dass eine erhebliche Reduzierung der Lärmemission und des Energieverbrauchs erreicht wird. Durch die präzise räumliche Dosierung können Hot Spots ganz gezielt gekühlt und damit die Ofenlaufzeiten bis zu einer Reparatur verlängert werden.

Kiln shell cooling by water evaporation, controlled by infrared temperature measurement

Ofenmantelkühlung durch Wasserverdampfung, geregelt durch Infrarot Temperaturmessung

1 Introduction

The operation of rotary kilns in cement plants that are located close to residential areas is increasingly associated with difficulties, at least in densely populated Europe. The noise generated by cooling fans is regarded by the local residents as very annoying, especially at night. As a consequence there is an increase in the official requirements for noise protection. The sharply rising energy costs mean that the operation of the fans represents a cost factor. Due to the increasing use of secondary fuels with fluctuating energy content there is also an increase in the demands made on the precision and dynamics of the cooling system and its control.

In discussions about how to deal with these problems the question was raised as to whether cooling the kiln shell with water instead of air could be a serious alternative. Simple trials had been carried out repeatedly in the past by various operators and plant manufacturers but in most cases the results were unsatisfactory because, as a rule, the kiln shell was cooled too sharply at the water-cooled point and had then contracted. This also caused stressing of the refractory lining, so the trials were stopped.

2 Properties of the water cooling system

However, a controlled water cooling system has several fundamental advantages, such as:

- low noise level
- high cooling effect
- low consumption of electrical energy
- ability to apply precise cooling to hot spots

The planning and design of this type of cooling system requires answers to several questions:

- How much water will be required?
- Can the cooling effect be sufficiently accurately adjusted?
- How will the kiln shell react to constant exposure to moisture?
- How much lime will be deposited if the cooling water contains lime?
- How will the cooling be affected by limescale on the kiln shell?
- What are the costs?

3 Thermal energy flows at the rotary kiln shell

Information about how much heat is typically dissipated through the kiln shell is needed to answer these questions. A typical kiln in Germany with the following data will be considered:

- Production: 3000 t/d
- Fuel energy requirement: 3200 kJ/kg
- This gives a thermal energy of: 111 MW that must be introduced into the kiln feed.

This examination does not take any losses into account. With rotary kilns the largest thermal loss mechanisms lie in the clinker cooler and in the preheater tower. The thermal energy actually introduced by the burner is nearer to 140 MW.

This gives rise to the questions:

- How much thermal energy is dissipated through the kiln shell?
- What is the mechanism of this dissipation?

For a kiln with fan cooling the heat is dissipated from the kiln shell in two ways:

- by thermal radiation
- by forced convection due to the fans (there is then no free convection)

3.1 Thermal radiation

Basically, every hot body emits thermal energy to the surroundings by radiation and also absorbs thermal energy from them. The net flow of thermal energy is described by the Stefan-Boltzmann law:

$$P_R = \sigma \cdot \varepsilon_O \cdot A_{MO} \cdot (T_O^4 - T_U^4) \qquad (1)$$

P_R = radiation power
σ = Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W/(m² K^4))
ε_O = kiln emissivity = 0.8
A_{MO} = surface area of kiln shell [m²] (per m length)
T_O = kiln shell temperature
T_U = ambient temperature

The thermal energy dissipated by thermal radiation per metre of kiln length calculated from Equation (1) is shown in Fig. 1 for a kiln with a diameter of 5 m as a function of the surface

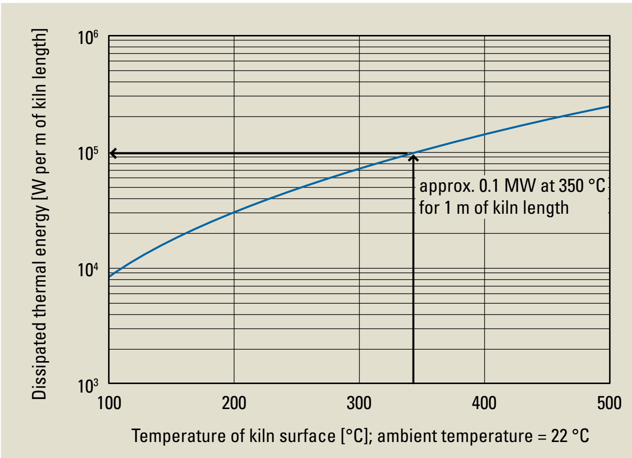

Figure 1: Thermal energy dissipated from the kiln by radiation

temperature. The ambient temperature was assumed to be 22 °C (= 295.16 K).

Integration of these values over the length of the kiln gives the total thermal energy dissipated from the kiln shell by thermal radiation. The kiln will also always dissipate this thermal energy after other cooling methods are applied and the particular surface temperature is established. This quantity is therefore only indirectly affected by other methods of cooling.

3.2 Forced convection

The amount that is, or has to be, dissipated by the fan cooling depends on many individual parameters of the kiln and the surroundings. In practice, the fan cooling power that is required to achieve a predetermined axial temperature profile is obtained from the cooling air flow and its temperature rise when the air passes over the kiln:

$$dV = \frac{dQ}{c_p \cdot \rho \cdot \Delta T} \qquad (2)$$

dV = air volume flow for dissipating the heat [m³/s]
dQ = thermal energy [kW]
c_p = specific thermal capacity of air [kJ/(kg·K)]
ρ = air density [kg/m³]
ΔT = temperature difference (exhaust air – incoming air) [K]

The air has a low thermal capacity and the "interaction time" is short during forced convection, which also means that the temperature rise that the air experiences on contact with the hot kiln surface cannot be very large, resulting in substantial air volume flows.

❱ Fig. 2 shows the air volume flow calculated from Equation (2) that is needed to dissipate a predetermined amount of thermal energy for four different temperature differences between the incoming air and the exhaust air.

In preliminary trials on the kiln at the Ennigerloh cement plant belonging to HeidelbergCement AG it was found that the fans that cool the central part of the kiln generate an air volume flow of about 150 000 m³/h. Using equation 2, we can calculate the dissipated thermal energy:

$$dQ = dV \cdot c_p \cdot \rho \cdot \Delta T \qquad (2a)$$

The blue line in Fig. 2 shows that an air flow of 150 000 m³/h that experiences a temperature rise of 40 K can dissipate approximately 2 MW of thermal energy. In order to achieve the same cooling rate by evaporation of water the shell surface must be hot enough to evaporate the water very quickly. This is the case with rotary cement kilns.

4 Cooling by water evaporation

Water is a very efficient cooling agent if it is supplied with enough energy to evaporate it, i.e. there is a phase transition from liquid to gas. Under isobaric conditions the energy of evaporation of water is the same as the evaporation enthalpy, and is given by:

$$\Delta H = \Delta U + p \cdot \Delta V \qquad (3)$$

ΔH = evaporation enthalpy of water (2.26 MJ/kg at standard pressure)
ΔU = internal energy (water evaporation)
p ΔV = displacement work against the air pressure

❱ Fig. 3 shows the quantity of water in l/s and m³/h calculated from Equation (3) that is needed to dissipate 2 MW of thermal energy during evaporation.

The diagram shows that on average only 0.9 l/s water must be distributed over the surface of the kiln to be cooled and also be evaporated there to achieve the required cooling effect of 2 MW. For a kiln with a diameter of 5 m and a length of 60 m (= 942.5 m² surface area) this gives

0.96 ml/(m²s) = 3.4 l/(m²h),

i.e. an extremely small quantity of water, that has to be distributed over each square metre per second. However, it is assumed here that the entire surface of the kiln is sprayed with water all the time, which cannot be achieved under the industrial conditions of a rotary cement kiln.

4.1 Precise metered application of water with flat fan nozzles

Small flat fan nozzles, which are lined up along the kiln axis and spray onto the rotating kiln shell (❱ Fig. 4), are used to provide a reliable and controlled spray of this small quantity of water onto the surface.

The water jet is spread out in the axial direction with an opening angle of 60 degrees and is very flat (≈ 5 to 15 degrees) in the radial direction. The required water flow is then obtained from the rotational time of the kiln and the width of the water jet when it strikes the kiln.

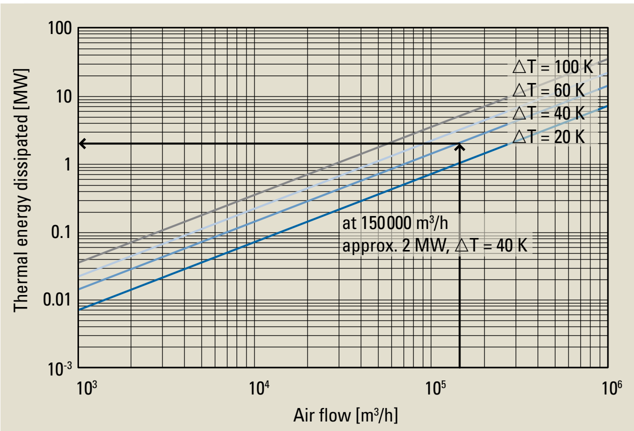

Figure 2: Thermal energy dissipated from the kiln by forced air cooling

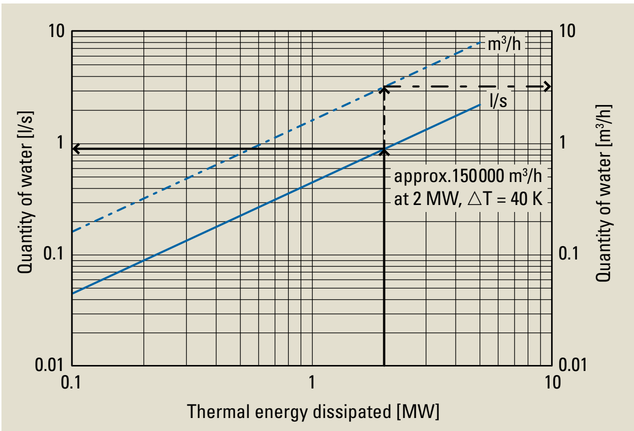

Figure 3: Thermal energy dissipated from the kiln due to evaporation of water

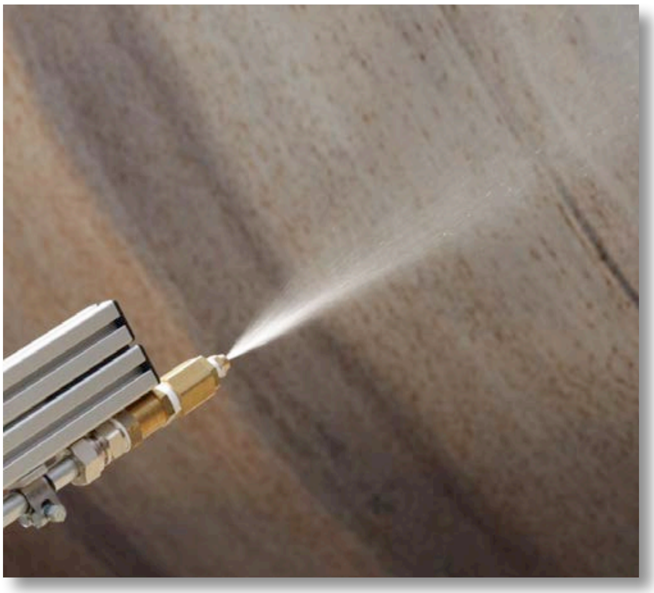

Figure 4: Flat fan nozzle for controlled water dosage

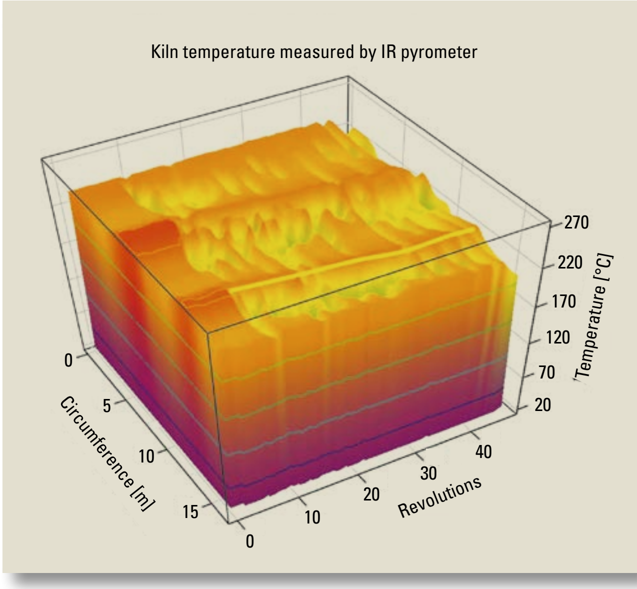

Figure 6: Cooling down a hot spot; temperature trend over a kiln segment

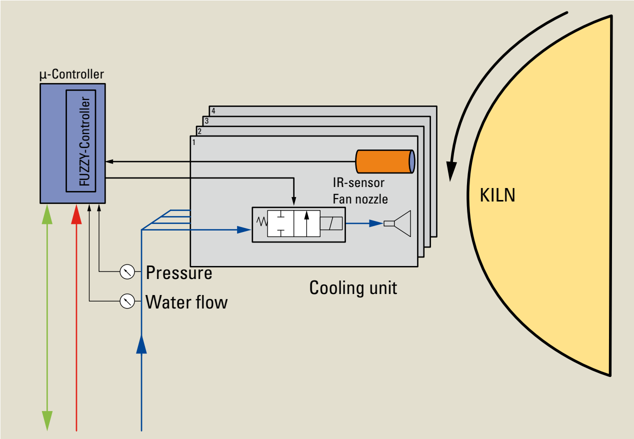

Figure 5: Cooling unit with flat fan nozzle, IR sensor and FUZZY controller

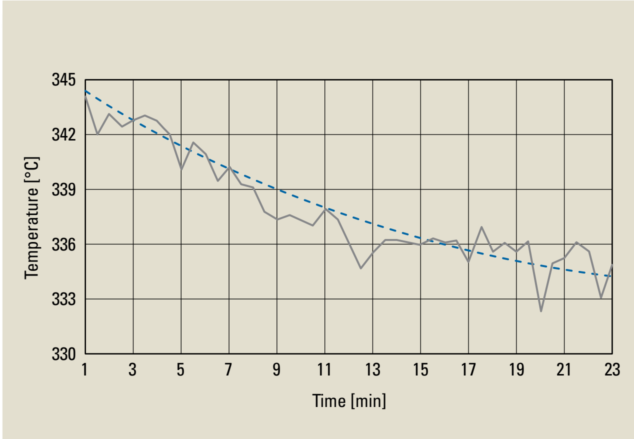

Figure 7: Avoiding mechanical stress by using moderate cooling rates (≈ 0.5 K/min)

4.2 IR pyrometer for controlling the amount of water

This mode of operation does mean that each point on the kiln is only sprayed very briefly with a correspondingly larger quantity of water and is then only sprayed again after one revolution (for example only after 30 seconds). However, the thermal inertia of the kiln is so large that uniform cooling of the kiln surface is still achieved. In fact, the amount of water that passes through the nozzle is chosen to be significantly larger than would be necessary for stationary cooling. A solenoid valve that is actuated by a micro controller is located before the nozzle. This allows the effective amount of water that is applied to the kiln shell to be adjusted over a wide range. An infrared pyrometer, which measures the surface temperature of the kiln shell before it rotates into the nozzle area, is also located before each nozzle (› Fig. 5).

The surface temperature passing in front of the pyrometer at any given time is measured continuously and an intelligent controller then opens or closes the solenoid valve appropriately. Several of these "cooling units", consisting of solenoid valve, nozzle and pyrometer, can be placed alongside one another so that large sections, or the entire kiln, can be covered if necessary. The target temperature for each nozzle can be set individually so that it is also easy to set an axial temperature profile for the kiln.

4.3 Selective cooling of hot spots

The unit does not just allow the kiln to be kept at a predetermined temperature. Hot spots that have formed can be cooled more strongly, and very selectively, than the surrounding area. This allows the hot spot to be brought back to the temperature of its surroundings, which significantly reduces any mechanical stresses in the kiln shell and brickwork. The 3D plot in › Fig. 6 shows the temperature signal from the pyrometer for a kiln segment in which there are two hot spots.

In each case, one revolution is plotted along the short axis ("shell circumference") and the individual revolutions are plotted one after the other along the long axis ("number of revolutions"). The z axis corresponds to the temperature. The two hot spots are clearly visible in the diagram. The cooling unit was switched on after a short time and the temperature of the hot spots was lowered while the rest of the surface essentially maintained its temperature. › Fig. 7 shows a section through the 3D plot along the yellow line. The number of revolutions from Fig. 6 has been converted into minutes for Fig. 7.

The supply of water for the hot spot was adjusted by the controller so that the cooling took place at a moderate rate of about 0.5 K/min in order to avoid stresses caused by cooling too rapidly. However, the cooling process could be accelerated by an increased supply of water.

5 Effect of the water cooling on the kiln shell

The use of water for cooling the kiln gives rise to three particular questions:

- Will the kiln shell be damaged by constant contact with water?
- How thick is the limescale that is left by the water (which can be expected to contain lime) after it has evaporated?
- What effect does the limescale have on the kiln operation, especially on the dissipation of heat?

5.1 Constant water contact

As far as the first question is concerned there was still insufficient long-term experience available when this article was published. Information from the Materials Science department of FH-Aachen indicates that there is no risk of damage to the metal provided the water cooling is used at kiln shell temperatures below 600 °C. It must also be borne in mind that the use of flat fan nozzles with very low opening angles in the direction of rotation means that, even with constant spraying, each point on the kiln comes into contact with liquid water for only a very short time as the amount that is sprayed on evaporates immediately. An opening angle of 10 degrees in the direction of rotation and a distance of 60 cm between the nozzle and the kiln give a contact time of only about 0.2 s for a kiln with a diameter of 5 m and a rotation time of 30 s. This means that during one revolution the water cooling system brings each point into contact with water for only 1/150 of the entire time. For continuous operation of the kiln for 365 days this ratio corresponds to a "wetting time" of 2.43 days.

5.2 Limescale

Water with a hardness of 11.2 dH (German degree of hardness), corresponding to 0.2 g/l lime ($CaCO_3$), was assumed for estimating the limescale. On the assumption that all this lime is deposited on the kiln in spite of the short contact time this gives an average increase in the layer of limescale of about 2.5 mm per year for a kiln with a diameter of 5 m and a length of 60 m that is sprayed on average with 1 l/s water.

In order to determine the rise in temperature that would be caused by such a layer of limescale on a kiln shell it is necessary to consider two effects:

- the conduction of heat through the particular material
- the thermal radiation from the surface of the material

5.3 Effect of the limescale on the temperature

The temperature gradient in a material that is hot on one side and cold on the other can be calculated easily using the thermal resistance:

$$R_{th} = \frac{l}{\lambda \cdot A} \tag{4}$$

R_{th} = thermal resistance [K/W]
l = thickness of the material [m]
λ = thermal conductivity [W/(m·K)]
A = cross-sectional area

The temperature difference is then obtained in analogy with Ohm's law for electricity from

Table 1: Thermal conductivity properties of the kiln wall

Material	Thermal conductivity [W/(m·K)]	Thickness [mm]	Thermal resistance [K/W]	ΔT for 1 W thermal energy [K]
Brickwork	2.5	300	1 200	1 200
Steel	58	50	8.6	8.6
Limestone	1.9	2.5	13.2	13.2

$$\Delta T = R_{th} \cdot P_{th} \tag{5}$$

ΔT = temperature difference across the material
R_{th} = thermal resistance [K/W]
P_{th} = thermal energy transported [W]

The temperature difference across the brickwork in, for example, the sintering zone can be obtained initially from the simple premise that the brickwork has a temperature of 1 540 °C on the inside of the kiln and a temperature of about 340 °C at the contact surface with the steel shell. ΔT is therefore 1 200 K and the thermal energy transported is 1 W per cm^2. This thermal energy must be transported through both the steel and the limescale; the thermal contact resistances have been ignored here.

For the materials being considered here (brickwork, steel and limestone) this gives the values listed in ❱ Table 1 ($A = 1\ cm^2$). The thermal radiation at the external surface of the kiln shell is in fact improved by the limescale as the radiation coefficient of rusty steel lies between 0.7 and 0.88 while for limestone it is 0.95. This means that even with a 2.5 mm thick layer of lime a temperature rise of only about 13 K can be expected at the point of contact between brickwork and steel shell. This constitutes only about 0.1 % of the temperature difference across the brickwork, i.e. it has no significant effect. As already said, this applies if the entire limestone content of the water is actually deposited on the surface of the kiln. ❱ Fig. 8 shows a cooling unit consisting of four nozzles with pyrometers and a control unit at a kiln, and ❱ Fig. 9 shows an area of kiln surface that has been cooled for several weeks with water containing limestone; the layer thickness is 0.1 to 0.2 mm.

6 Noise emission

Finally, the noise emissions from the fans were compared with those of the water nozzles. The noise emission from a water jet that sprays about 50 ml/s is approximately 63 db(A), while the fans generate about 105 db(A). This means that the noise nuisance can be very substantially reduced by water cooling.

7 Operating costs

The operating costs for a water cooling system depend mainly on the cost of the cooling water, which can vary sharply depending on the location. However, industrial water or a reservoir is usually available, so the cost of the water is low. The power costs are also very low as the electronics with power units for actuating the on-off valves have an installed load of only 10 W/m of kiln length.

Realistically, the power that is required for maintaining the water pressure for the nozzles must also be included in the calculation. This is also highly dependent on local factors so

Figure 8: Cooling unit with four nozzles, four pyrometers and a controller

Figure 9: Limescale on a kiln surface after several weeks in operation

it is difficult to provide any generally valid data. However, an estimate can be made using the simple premise that if a water cooling system is to be operated continuously it is sensible for operational reliability to install reservoir tanks with volumes of a few cubic metres in, for example, the preheater tower. This will maintain the water pressure for an adequate period if the water supply fails. Assuming a lift height of 50 m then 0.14 kWh is required to pump 1 m^3 water to this height. If it is also assumed that all losses and the efficiency of the pumps taken together will double the power requirement then this still only gives 0.28 kWh/m^3 water, so only 1 kWh power is required for the assumed 3.4 m^3/h water for cooling a kiln.

8 Final comment

At the moment there are five units of the first series, each with four nozzles, in use in various cement plants. They are used mainly for cooling hot spots. Experience so far indicates that the expectations are being completely fulfilled:

- The noise emission is greatly reduced when compared with a fan.
- The power consumption is very low.
- The metered water addition controlled by IR sensors means that the kiln shell temperature can be brought to a target temperature both axially and radially and then kept there.
- Hot spots can be cooled more strongly and very selectively so that any mechanical stresses in the shell are reduced.
- Coating formation can be initiated if there is damage to the brickwork.
- If there is more serious damage to the brickwork then the cooling units have been able to extend the kiln's running time and avoid premature production stoppages.