The thermal field analysis of the rotary kiln for the cement plants by means of the image processing techniques

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Abstract. The implementation of the image processing techniques for the analysis of the thermal field images captured with infrared scanners from the shield of the rotary kilns increase the quality of the information required for the optimization, monitoring and failure prevention of the kiln. In this work, authors presented a method that implement advanced algorithms such as the Radon transform, the segmentation and labeling of images for estimating the space-distributed, parametric model of the kiln's thermal field. The aim of the investigation is analyzing the similarities/differences between the thermal profile of the kiln and the kiln's maintenance events. The implementation of the proposed method proved that the correlations between the changes of the thermal profile and the renewal of the thermal coating of the kiln may be well emphasized. In this perspective, this method is suitable for building a thermal profile of the kiln during an entire maintenance time span.

1. Introduction

Since decades, the rotary kilns are used for cement and lime production. Recent estimations count that the cement production is set to increase between 12% and 23% by 2050. In addition to its economic importance, the cement manufacture rises environmental concerns due to the high energy consumption, the release of greenhouse gases, NOx, SO2, and particulates etc.

The enterprises in the cement industry spend a large amount of financial and technological resources for the protection of the environment aiming to reduce the greenhouse gas emissions and particulates according to the environmental regulations.

In this perspective, the improvement of the thermal efficiency of the kiln, the failure prevention of the thermal coat and the decrease of time required for the adjustments of the flame length at the startup of the process are specific measures that allow the reduction of specific costs and the improvement of the quality of the final product.

Considering the importance of the optimal rotary kilns operation, designers, manufacturers in the cement industry as well as researchers in the field continuously improve the methods and apparatus dedicated to the observation, prediction and control of the rotary kilns (figure 1).
The processes and phenomena that occur during the clinker manufacture are well documented; a referential book is [1]. In the technical literature, many articles are dedicated to the process control and monitoring of the rotary kiln in the cement industry.

The typical control strategies, meant to substitute the manual operator are [2]:
- the expert-based solutions;
- the model predictive control.

The expert-based methods, such as the fuzzy logic, proved useful for nonlinear processes (e.g. the burning process). In model predictive strategy, the plant dynamics are described by an explicit predictive model.

The model predictive control computes the process inputs and the control action to optimize the future plant behavior over the prediction horizon in accordance with a given objective function. The formulation is solved at each time-step using updated measurements from the process. Models such as black-box and gray-box may be used within the model predictive control formulation.

The method captures the local behavior of the plant as close to the reference as possible. In this work, the authors used a system identification approach and focused on the thermal processes within the rotary kiln. In a previous work [3] a time-domain flows' dependencies of the materials and particulate in a rotary kiln for solid waste reclamation were investigated. In this work a space-distributed model of the thermal field is taken into account, based on the method firstly implemented in [4].

The organization of this work is as follows. In Chapter 2, the implementation of the image processing method for the analysis of the kiln's thermal field from scanner images is presented. Two implementations of the proposed method, correlated with a maintenance event of a rotary kiln are presented in Chapter 3. In Chapter 4, the results and their interpretations are detailed.

2. Methods

2.1. The manufacture of the cement clinker

The rotary kilns are combustion chambers mainly used for cement manufacturing, solid and semisolid hazardous waste treatment [1].

The main part of the rotary kiln is an inclined cylinder which rotates slowly to accomplish mixing of the materials and to expose all surfaces and substances to heat and oxygen, figure 2.

The flame residence time is of the order of 2 to 5 seconds and the flame temperature is of over 2000°K. The material residence time within the kiln is typically greater than an hour. This feature allows maintaining the uniformity of the quality of the final product.

However, the quality of the product may be affected by various factors such as the variance of the inlet materials properties, the fuel, the status of the thermal insulation of the shield, as well as other physical and chemical factors.

In this respect, various researches were made in the area of the control and observation of the complex physical and chemical processes that occur within the rotary kilns during their operation [1], [5, 6].
2.2. Knowledge models vs. parametric models for the cement rotary kiln

The clinker manufacturing consists in the transformation of a mixture of raw materials (limestone – CaCO₃ and clay) into alite (Ca₃SiO₅). The chemical reactions required for the process evolves on stages onto three zones of the rotary kiln. In table 1 the space-distribution and the corresponding temperatures related to the chemical reactions occurring to the clinker manufacturing are presented.

Table 1. The clinker manufacturing in the rotary kiln. The correlations between the chemical reactions and their corresponding temperatures.

| No. | Kiln zone | Chemical reactions | Temperature (°C) |
|-----|-----------|--------------------|-----------------|
| 1.  | Decomposition | | |
|  | $CaCO_3 = CaO + CO_2$ | 600-900 |
|  | $CaO + Al_2O_3 = CaO \cdot Al_2O_3$ | 800 |
|  | $CaO + Fe_2O_3 = CaO \cdot Fe_2O_3$ | 800 |
|  | $CaO + CaO \cdot Fe_2O_3 = 2CaO \cdot Fe_2O_3$ | 800 |
|  | $3(CaO \cdot Al_2O_3) + 2CaO = 5CaO \cdot 3Al_2O_3$ | 900-950 |
| 2.  | Transition | | |
|  | $2CaO + SiO_2 = 2CaO \cdot SiO_2$ | 1000 |
|  | $3(2CaO \cdot Fe_2O_3) + 5CaO \cdot 3Al_2O_3 + CaO = 3(4CaO \cdot Al_2O_3 \cdot Fe_2O_3) = 5CaO \cdot 3Al_2O_3 + 4CaO = 3(3CaO \cdot Al_2O_3)$ | 1200-1300 |
| 3.  | Sintering | | |
|  | $2CaO \cdot SiO_2 + CaO = 3CaO \cdot SiO_2$ | 1350-1450 |

Ref. [1].

The science-based models of the clinker manufacturing process in the rotary kiln refer to the interaction between the ensemble of transport processes and chemical phenomena that occur into the kiln during operation. The transport processes refer to the bed phenomenon, the transverse and the axial motion of the bed. The physical phenomena refer to the free board aerodynamic phenomena, the granular flows in the kiln, the particle mixing and segregation, and the heat transfer processes. The chemical phenomena refer to the chemistry of the cement process and to the combustion chemistry of the fuel used. Documented knowledge-based models for these complex processes are presented in [1]. Although, the knowledge-based models are effective to the experimental data, the complex interactions that occur during the real-life manufacturing of the clinker into the kiln are difficult to predict by means of these models. The system identification approach and its related parametric time-domain models are more
suitable for on-line observations, predictions and control, [3] due to the following reasons: (a) the time-
domain models are related to the observed data and to predefined abstract classes of models that are not
related to the nature of the processes depicted, (b) the models are adaptive in the sense that the values
of the coefficients are estimated each time a new data set is acquired from the process and (c) by adopting
a time- and space-distributed model for the process the modeling of the overall interactions between the
processes and transport phenomena may be observed.

2.3. The implementation of the image processing techniques for estimating the parametric models of
the rotary kiln
In the flowchart depicted in figure 3, the images of the kiln’s thermal spectra acquired from the scanner
– (3), are decomposed on levels of temperature – (4). The result of the decomposition is a set of binary
images. Each binary image is treated in the loop (5) as follows: in the module (6) the regions at the given
level of temperature are detected; each region within the image is labelled recorded – module (7).

![Flowchart of the proposed method and its software implementation.](image)

After all levels of temperature are processed, the geometrical features of regions i.e. the surface
coordinates, the width and the length of the outer box frames and the coordinates of the regions’ centroids
are estimated – module (9). These results are used in module (10) for the computations of the actual
values of the 5 – order parametric model that depicts the thermal profile of the kiln – module (10). The
resulting thermal model is used in module (11) to produce the estimate of the thermal losses and the
thermal efficiency of the kiln. The thermal losses were estimated with the assumption that the heat
transfer from the shield to the environment (air) is made by radiation.
3. The experiment

3.1. The experiment components, apparatus and software
The experiment was carried on several sets of experimental scans acquired from the process at the “CRH Ciment Romania” – the Hoghiz Cement Factory. The technical features of the rotary kiln at the Hoghiz Cement Factory are given in table 2.

| Denomination                      | Units | Values       |
|-----------------------------------|-------|--------------|
| Kiln length                       | m     | 97.6         |
| Kiln diameter                     | m     | 6.04         |
| Kiln angular speed                | rpm   | 2.1          |
| Kiln fuel (a mix of coke, coal and powder waste) | t     | 1 to 12      |
| Kiln production capability        | t     | 3600         |

The shell of the kiln was monitored with the thermal scanner of type Infrared Kilnscan. The main features of the Infrared Kilnscan scanner are: continuous full temperature map, with a true one-brick resolution, hot spots early warning before damage, monitoring and extension of refractory lifetime, reliable preventive maintenance scheduling, scanner’s data direct linkage to the Plant Control System.

The inside kiln temperature was also monitored via a Pyroscan - Ruggedized HDR Pyrometric Camera. The data from the scanner was transmitted to the control room through an optic fiber link to avoid electromagnetic interference. The monitoring system was also provided with hot spot detection but produced poor predictions of the thermal process’s evolution with time. The software applications were written in the Python environment [7].

3.2. The organization of the experiment
The organization of the experiment was as follows.

Observations of the thermal spectra at the surface of the kiln at two different moments of time were made. The first observation – Test 1 – was made before the deadline of the maintenance cycle of the kiln. The second observation – Test 2 – was made after the thermal insulation of the kiln had been renewed. In figure 4 an example of the thermal spectra image acquired from the thermal camera KilnScan captured within the tests is presented.
The images acquired from the scanner with threshold on levels of 10 Celsius degrees as presented in figure 5.

For each level of temperature, the binary image was extracted and processed according with the procedure depicted in Chapter 2. The binary image at 180 Celsius degrees is presented in figure 6.

4. Results and discussions
In this section, the interpretation of the image processing analysis is presented as follows:

- the analysis of the estimations of the Radon transform on the (Od) direction of images;
- the 5th – order polynomial approximation of the surface versus temperature dependency;
- the power-losses versus temperature estimate.

4.1. The estimations of the Radon transform on the (Od) direction of images
An example of the estimates of the Radon transforms from the acquired images is depicted in figure 7. The comparison of the estimates at test 1 and test 2, provides the followings:

- the levels of projections are of the form of random variables;
- the levels of the projections corresponding to the input side of the kiln (the left side of each image) are statistically higher than the levels corresponding to the output side of the kiln (the right side of each image);
- the levels of the projections corresponding to the middle area are in the middle range of values;
- the similarity between the projections levels at test 1 and test 2 may not be made at the samples level thus one must use a statistical approach.

**Figure 7.** The Radon transforms onto the (Od) axes of images presented in figures 6. Test 1 – to the left and Test 2 – to the right.

To emphasize this idea, the histogram (or the empirical probability function) of the Radon transforms values for the Test 1 and the Test 2 are depicted in figure 8.

**Figure 8.** The Histograms of the Radon transforms from figure 7: Test 1 – to the left and Test 2 – to the right.

The histogram from Test 1 gives a sample mean of 19.89 and a variance of 16.62 and the histogram from Test 2 gives a sample mean of 19.89 too and a variance of 22.05. This result proves the intensities of projections are statistically higher in Test 2 than in Test 1.

4.2. The approximation of the surface versus the temperature dependencies

The surface versus temperature dependencies are depicted in figure 9.

**Figure 9.** The dependencies of the surfaces versus the temperature: Test 1 – to the left and Test 2 – to the right.
The 5th-order polynomial approximation of the estimates features the same profile. The given polynomial and its coefficients may be interpreted as a parametric model of the thermal process in the kiln and thus may be used for predictions.

For both tests there are three local extremes: one local maximum around 200°C, one local minimum around 275°C and another local maximum around 350°C.

At Test 1, the amount of surface in the low range of temperature is higher and the amount of surface in the high range of temperature is lower than the corresponding ranges in the Test 2.

One may assess that the kiln was less heated during Test 1 than Test 2. However, the given profile proves that the improvement of the thermal insulation made before Test 2 has reduced the values of the temperature at the surface at the kiln.

A numerical comparison between the given tests regarding the local max/min values of temperature and surface is given in Table 3.

| No. | Kiln’s zone | Test No. | Temp. (°C) | Surfaceb (pixels) | Temp. (°C) | Surfaceb (pixels) | Temp. (°C) | Surfaceb (pixels) |
|-----|-------------|----------|------------|-------------------|------------|-------------------|------------|-------------------|
| 1.  | Decomposition | Test 1 | 211.75 | 152513 | 283.5 | 33939.7 | 329.0 | 56887.1 |
| 2.  | Transition | Test 2 | 206.50 | 116312 | 273.0 | 71290.2 | 304.5 | 75099.4 |
| 3.  | Sintering | Test 1 vs Test 2 | 2.48% | 23.7% | 3.85% | -110.05% | 7.45% | -32.01% |

a The local max/min values are taken from figure 9;
b The pixels count is related to the dimensions of the image in figure 5.

One may observe there are similar max/min values of temperature at all regions of the kiln for both tests. However, the difference of surfaces of the transition region at Test 1 and its corresponding at Test 2 is (-110.05)% of the surface at the transition region at Test 1.

The dependencies of the power losses at the surface of the kiln with respect to the temperature are depicted in figure 10.

The estimations prove that the power losses at the sintering region decreased with (-23.45)% from Test 1 to Test 2 and the power losses at the transition region increased significantly with 99.59%. In the decomposition zone, the power losses also increased with 24.82%. The corresponding values of temperature didn't change significantly.

The integral of the power losses density with respect to the temperature estimates the total power losses of the kiln. The comparison proves that the efficiency of the kiln at Test 1 is lower than its counterpart at Test 2.

The local max/min values are presented in Table 4.
Table 4. The dependency of the power-losses vs. temperature – the local max/min valuesa.

| No. | Kiln’s zone | Test No. | Temp. (°C) | Power (kW) | Temp. (°C) | Power (kW) | Temp. (°C) | Power (kW) |
|-----|-------------|----------|------------|-----------|------------|-----------|------------|-----------|
|     |             | Test 1   | 210.00     | 32373.60  | 281.75     | 9579.15   | 330.75     | 18790.10  |
|     |             | Test 2   | 211.75     | 24337.90  | 262.50     | 19118.90  | 313.25     | 23196.40  |
| 3.  | Test 1 vs. Test 2 | -0.83% | 24.82% | 6.83% | -99.59% | 5.29% | -23.45% |

a The local max/min values are from figure 10.

5. Conclusions
The cement manufacturing processes into the rotary kilns consists of a complex interaction between chemical, thermodynamic and mechanical processes. From the analysis point of view, the knowledge-based model of each component of this interaction is well documented in the literature. However, for online observations, monitoring and control, the above approach is less efficient. In this respect, the authors proposed implementing a parametric, polynomial model of the thermal power-losses surface distribution of the kiln. The values of the coefficients of the polynomial are determined with the least-squares algorithm in order to minimize the prediction errors.

Within this work, the proposed method was implemented onto observations of the thermal spectra of the rotary kiln at the “CRH Ciment Romania” – The Hoghiz Cement Factory. Two significant experiments – correlated with the maintenance cycle of the kiln – were taken into account. The comparison between the estimated power-losses of the kiln at the aforementioned tests, emphasized the possibility of detection of changes during the lifetime of the coating of the kiln. Further research intends to evaluate the power-losses profile of the kiln over an entire maintenance time-span that could allow evaluating the actual status of the thermal coating from measurements.

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