Thermal analysis of the rotary kiln through FEA

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Abstract: - This paper aims at analyzing numerical heat transfer in kiln clinker production in cement factory Deva, important processing equipment in the cement production. The importance of knowing this process aims to rationalize the consumption of raw materials and energy but also to get high standard finished products. We used QuickField software package Version 5.10.1 for analysis of thermal problems in a rotary kiln to obtain an optimal and efficient sinterization process. In this study, our objectives are to predict the temperatures in the inner surface/refractory and inner surface of bed before any variations in process parameters, to decrease the errors arisen from the operators, to increase the efficiency and finally decrease the process cost also the variation of inside temperature with flame temperature.

Key-Words: - FEA, modelling, heat transfer, rotary kiln, efficient operation, clinker.

1 Introduction
Today, Portland cement is the most widely used building material in the world with about 1.56 billion tones (1.72 billion tons) produced each year (Cement Association of Canada, 2001). Global economic situation sets more and more challenges to cement manufacturers both in our country and globally. Although the cement market in Romania has reached a high level with annual an increase up to 30%, the end of 2012 was faced with stagnation or at most an increase of 1-2% and in 2013 most likely cement market will record a standstill, because of demand, but also due to rising prices. It must be noted that the need to maintain producers on the market is due to more and more discipline regarding costs and optimizing them according tp technological efficiency and rationalization of raw materials and energy (Carpatcement Holding, 2013)

The main cement producers on the Romanian market are: Carpatcement (Bicaz factories, Fieni and Deva), Lafarge (Medgidia Hoghiz and Targu Jiu) and Holcim (Turda and Alesd). Carpatcement Holding hope for a rearrangement of the macroeconomic situation of the country starting this year and also for a market that depends on several conditions so that construction work can be started earlier than in 2012 (Carpatcement Holding, 2013).

The cement industry is actively engaged and committed to sustainable development — a philosophy that focuses on meeting our construction needs today without depleting future resources. Cement industry production process has a big impact on the environment which is why a lot of investment projects headed in this direction.

Process automation and information technology are industrial areas which offer the biggest and most satisfying challenges in terms of combining traditional engineering skills with technological innovation [4].

The demands on cement industry in relation to productivity, quality and price, means an ever increasing need to improve the quality products, to productivity increase improvement of products quality, modernization of the technological flow and environmental quality.

2 State of Art
Portland cement clinker is produced from a mixture of raw materials containing calcium, silicon, aluminum, and iron as the main elements. The mixture is heated in kilns that are long rotating steel cylinders on an incline. The feed of a typical cement kiln consists of limestone and other, mainly oxide and silicate based material, which typically contain calcium, magnesium and iron. The process goes through the raw material grinding, blending, precalcining, calcining (clinker formation), cooling and grinding of final product. In the preheating system, the raw material goes through preliminary steps, where the calcination of \( \text{CaCO}_3 \) and formation of calcium oxide takes place.

The material is fed from the top of the cyclone and move downward in counter stream with gas
resulting from the combustion process that flows through cyclone separator from lower levels to higher ones. Flow chart of clinker production is shown in Fig. 1, [12]. In this way the gas are cooling as raw material preheating and start the process of calcinations. Raw material in suspension separates the gas in each gear shift and gas reunited in the descent step. This process are repeating (separation - mixing) every step of unloading mix material exchanger to ensure good furnace heat transfer.

The calcination (transforming of raw material into clinker, the intermediate product used to produce cement) occurs in rotary kiln according to the four zones: calcination area, transition zone, clinkering zone and cooling zone. The kiln temperature needed for this process is about 1450 °C and flame temperature of approximately 2000 °C. [5]

The rotary kiln is divided into successive control volumes or cells [6]. The volume elements of the bed and the gas in the cells are described as open thermochemical systems, which transforms heat and mass with each other.

![Clinker production flow chart](image)

The clinker leaving the kiln enters the cooler rack which has two functions: to recover a larger amount of energy from the hot clinker to be used in the process and to reduce the clinker temperature to the right level for its later semi fabricated use for cement production.

Although there is a quite high level of automation and the control of installations for each stage of cement production from Deva Factory and monitoring using integrated systems there are many objectives which can do the efficiency growth.

Using the PLCs and expert systems has been brought forward to the board of the company, managing to deploy an expert system. Thus the technological process is carried out from the command room using the visualisation system ECS-Ntech and the PLCs Allen Bradley (kiln and cooler) and Siemens [12]. Through this system the attendant can overlook the performance of the technological process using the computer network. [1]

Correct measurement of the temperature on a kiln shell is essential for efficient operation of the kiln. ECS/CemScanner represents the state-of-the-art in kiln shell infrared scanning. The thermal detailed image and real-time monitoring of the ring formations in the kiln are set up. If obstacles prevent the scanner from viewing parts of the kiln shell, up to 8 infrared pyrometers can be installed to measure temperatures in these specific areas. [12] To obtain an optimal and efficient sinterization process both in terms of economy of materials and to obtain quality products, besides all the monitoring and control of rotary kiln temperatures we performed a thermal analysis using software QuickField.

### 3. Background

The finite element method FEM is used to solve complex engineering problem [2]. Engineers who need to model electromagnetic or thermal fields frequently turn to finite-element analysis (FEA), a numerical technique for solving field problems of all kinds [9]. The first step in finite-element analysis is to divide the analyzed configuration into small homogeneous elements. The model contains information about the device geometry, material constants, loads and boundary constraints [3]. In each finite element, a linear variation of the field quantity is assumed. The corners of the elements are called nodes. The goal is to determine the field quantities at the nodes. The Finite-Element Analysis technique solves the unknown field quantities by minimizing energy functional. The energy functional is an expression describing all the energy associated with the configuration being analyzed.

QuickField is a finite element analysis software package, a slick FEA for solving two or three dimensional field problems. From studies and evaluations conducted by a team of developers it is estimated that QuickField is easy and suitable for this problem. [11]

Compared to other FEA programs, QuickField has two main facilities: exceptional user-friendliness and blinding speed. The program has a typical
Windows interface, drop-down menus, and extensive help facility, and is equipped with many sample programs [11]. While the user has to understand something about the physics of the problem to successfully carry out a simulation, the mechanics themselves are straightforward. Even on a slow PC, users can construct and run models with tens of thousands of nodes, which make it practical to solve very complex models on modest platforms. The program itself is small, a few megabytes with various required files.

Heat-transfer equation for linear problems in rotary kiln is represented by the differential mathematical model of the thermal conduction [11]:

\[ \text{div}(\lambda \text{grad}T) + q - \rho c \frac{\partial T}{\partial t} = 0, \]

(1)

\[ \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) = -q - c \rho \frac{\partial T}{\partial t}, \]

(2)

where: \( T \) – scalar temperature; \( t \) - time; \( \lambda \) (\( y, r, z \)) - components of heat conductivity tensor; \( \lambda(T) \) - heat conductivity as a function of temperature approximated by cubic spline (anisotropy is not supported in nonlinear case); \( q(T) \) - volume power of heat sources, in linear case - constant, in nonlinear case - function of temperature approximated by cubic spline; \( c(T) \) - specific heat, in nonlinear case - function of temperature approximated by cubic spline and \( \rho \) - density of the substance.

4. Modelling of heat transfer with FEA

The clinker production process involves heat and mass transfer between the kiln, fuel, primary and secondary air, drying of raw material mix call flour, and calcining of \( \text{CaCO}_3 \) [6]. It is important to have a comprehensive understanding of these processes in order to: diagnose operational problems, improve energy consumption, increase production, reduce emissions, increase refractory life, improve the product quality and optimize kiln operations.

The given computer model of thermal processes, allows to calculate temperatures pattern both at a surface and inside a body [10]. The model allows to perform calculation heat transfer of a multy-layer ring structure of a body with a granular mixture - clinker, roasted inside it (Fig. 2). [7] The kiln body is coated with refractory brick and is analysing like a multy-layer body: shell, chamotte, air inside and clinker. There are three different heat transfer mechanisms in the rotary kiln, Fig. 2 [7].
The model is described through a multi layered with different properties model, that is the outside layer is formed of 2 layers and the inside of the kiln contains the gas, clinker and heat source. The geometric model is composed of blocks with different properties, in this case, it was assigned 4 blocks with material properties specified (air, chamotte, clinker, steel shell), Table 1. In each block the material properties was specified (thermal conductivity \( \lambda \) and volume power of Heat sources \( Q \)).

The model geometry was described by create vertex label with source specified (burner flame \( Q \)) and edge label with boundary condition specified that form boundaries of all subregions having different physical properties. We created two geometrical models.

### Table 1. Material properties in each blocks

<table>
<thead>
<tr>
<th>Block Label</th>
<th>Thermal conductivity ( \lambda_1 ) (W/K.m)</th>
<th>Thermal conductivity ( \lambda_2 ) (W/K.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>chamotte</td>
<td>0.165</td>
<td>0.165</td>
</tr>
<tr>
<td>clinker</td>
<td>1.2</td>
<td>0.1225</td>
</tr>
<tr>
<td>steel shell</td>
<td>22</td>
<td>22</td>
</tr>
</tbody>
</table>

Applied mesh is shown in Figure 3 and the field values at the nodes have been calculated.

Finite Element analysis is based on discretization of the area into the number of simple shapes, in case of QuickField – triangles. Accuracy of the results highly depends upon the finite element mesh density and quality. Moreover, in complicated cases problem solution on the non-adequate meshes may not converge. That’s why the mesh generation is one of the most important operations in all practical FEA applications. QuickField Model Editor is equipped with very efficient mesh generators. But sometimes, then the geometry was really complex, smooth mesh generation required many manual adjustments. Improved mesh building algorithms of this version 5.10 assure automatic generation of the smooth meshes even in the most complicated cases, which allows good results of the model.

We have built the mesh in all blocks participating in field calculation. Flame positioning for example can be predicted in multi-dimensional models rather than used as an input. In one of the models the flame position is concentrated in the center of the section and in a point of the upper half of the section in other model, Fig. 3. Each model was individually tested and where appropriate, was compared to experimental results.

The first option has been created with a digitization network of 5 blocks in which the heat source is concentrated and defined by a block unlike the second option with four blocks in which the heat source is defined by a labeled vertex with boundary condition and source specified through temperature value \( T = 2000K \).

Edge label with boundary condition specified for two scenarios are shown in Table 2.

### Table 2. Boundary conditions applied

<table>
<thead>
<tr>
<th>Edge Labels</th>
<th>Temperature ( T_1(K) )</th>
<th>Temperature ( T_2(K) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer</td>
<td>293</td>
<td>293</td>
</tr>
<tr>
<td>Inner</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bed surface</td>
<td>1450</td>
<td>1000</td>
</tr>
</tbody>
</table>

Because thermal conductivity function of temperature in nonliner case, we have carried out two scenarios considering the conductivity variation, \( \lambda = \lambda(T) \) of clinker and results are shown in Fig. 4 for \( \lambda_1 \) and in Fig. 5 for \( \lambda_2 \).

The energy to raise the temperature and drive endothermic reactions is from the combustion of a range of fuels such as natural gas, coal and more and more alternative fuels.
4.2 Temperature distribution inside

The feasibility of simulating heat transfer 2D using a common, finite element modeling package QuickField was tested. The aim was to recreate well known, but difficult to simulate, interactions between thermal transfers in multy layer structure.

For the test application, QuickField was chosen for the following reasons: the Heat Transfer module is used to analyze the temperature distribution in static and transient heat transfer processes; nonlinear or anisotropic properties; boundary temperature and heat fluxes and boundary conditions with convective/radiative terms.

Temperature distribution $T$, in vertical section and vectors of heat flux $F$ are presented in Fig. 5 when it was chosen a temperature inside about 1450°C for surface of bed.

The contour definite for calculus of quantities value is shown in Fig 6 and also isotherms.

The same contour was chosen for temperature of $T = 1000K$ and quantities value has been collated, Fig 7. We have applied two values on the boundary conditions for the temperature inside the kiln on the clinker surface $T_1$ and $T_2$. The combustion to the fuel is assumed to occur at a point two meters into the kiln and is complete at a point 32 m into the kiln. The temperature profile at inside the kiln follows a parabolic function [7].

4.3 Results

To analyze the results obtained on the contour defined in Fig. 6 and Fig. 7 at temperatures $T_1$ and $T_2$ we have performed parametric analyzer with LabelMover. We have specified the values which we want to optimize and start optimization process for some physical quantities.

We have calculated with Harmonics Browse the plot for temperature values and amplitudes for the two boundary conditions, $T_1$ and $T_2$. Harmonic and linear approximation of the temperature variation (K) on contour inside the kiln (m) that corresponds at the whole period, are shown in Fig. 8. The plot of temperatures approximation for the value of $\lambda_1$ without conditions imposed for the temperature of clinker bed surface, only temperature source, like $T=2000K$, has been raised.

This add-in allows us to calculate and view harmonics (that is, phases and amplitudes for Fourier series) for any displayed quantity related to the currently selected contour.

The graph of temperature variation, obtained from model described has been presented in Fig. 9. We stopped at the results that are comparable with the results achieved from measurements. The following results are retrieved: temperature, heat flow, thermal gradients, and total heat loss on any
given part and other whole inner surface of quantities for clinker bed.

Fig. 9. Temperature variation on bed surface

Data achieved from a full-scale cement kiln at Deva factory are comparable to results achieved with the software used. The best approximation is achieved on the clinker surface when the temperature of the heat source is taken from the pyrometer inside the rotary kiln like in Fig. 10.

Fig. 10 Data from pyrometer measurements inside the kiln

5. Conclusions

The validation of any model is extremely importance for the effective use of the model as a design tool. Validation to heat transfer has been done using full scale kilns at Deva cement factory.

In further development of the model the aim is to incorporate not only thermal profiles for the rotary section of dry process kilns but the effect of chain systems in long wet kilns including dust entrainment through the chains.

We see significant temperature increase close to flame of burner (e.g. T = 1810K). However, the heat source can be changed to accommodate longer less intense flames. To maximize refractory life, it is essential to avoid flame impingement on the refractory lining. Therefore it is recommended to positioning burner system in order to avoid possible refractory failure in that region. Engineers can use the software to diagnose equipment problems.

References: