SIMULAREA PROCESULUI DE ARDERE ŞI A TRANSFERULUI TERMIC ÎN ZONA DE CLINCHERIZARE A CUPTORULUI ROTATIV▲

SIMULATION OF THE BURNING PROCESS AND OF THE HEAT TRANSFER IN THE FLAME AREA OF THE ROTARY KILN

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This paper presents a mathematical model for the heat transfer in the clinkering area of the rotary kiln. This problem can be solved in several ways. One simplistic approach would be to know the flame temperature in order to compute, among other secondary parameters, the temperature profile of the material. Another – much more practical – option is to know (to set) the temperature profile of the material over the length of the clinkering area of the rotary kiln, that further could be used to calculate the gas and kiln wall/shell temperature.

In this study it was consolidated this last alternative which requires the heating curve of the material (it is known/given the distribution of the material temperature in the rotary kiln, as necessary to obtain clinker quality). We then moved forward by implementing a broader approach, i.e. by assuming different amounts of fuel allocation over the length on the clinkering area; this distribution could be correlated with flame shape. Several coating width values were also included in simulation as an input parameter, thus contributing to broadening the options and to increase the realism level.

The model used a series of assumptions, limitations and simplifications. They are due to the complex nature of processes taking place in this area and are compulsory because the clinkering area could be considered independent and having a fixed length only under ideal conditions! In real life, complex interactions of material and energy with other parts of the clinkering plant can be easily identified.

În aceasta lucrare a fost dezvoltat un model matematic pentru zona de clincherizare a cuptorului rotativ de clincherizare. Această problemă poate fi rezolvată pe mai multe căi. O soluție facilă ar fi să se cunoască temperatura flăcării, pe baza căreia se pot calcula o serie de parametri derivați. O a doua variantă este aceea în care se impune distribuția temperaturii materialului pe lungimea zonei de clincherizare, care poate fi utilizată pentru calculul profilului de temperatură pentru gaze şi pereți.

În acest studiu s-a consolidat varianta în care se impune curba de încălzire a materialului (se cunoaşte/impune distribuția temperaturii materialului pe lungimea cuptorului, necesară pentru a obține nivelul de calitate dorit pentru clincher). Au fost utilizate o serie de distribuții de combustibil pe lungimea zonei de clincherizare. Aceste cantități pot fi corelate cu forma flăcării. S-a mers mai departe în creşterea gradului de realism al simulărilor prin introducerea de valori diferite pentru grosimea stratului de lipitură care se formează pe suprafața interioară a cuptorului.

În lucrare s-au folosit o serie de impuneri, limitări şi simplificări. Acestea sunt datorate caracterului complex al proceselor care se desfăşoară în această zonă şi devin necesare datorită faptului că zona de clincherizare poate fi considerată ca fiind independentă şi având lungime fixă doar în condiții ideale. În realitate există schimburi complexe de materie şi energie cu alte părți ale instalației de clincherizare.

Keywords: *modeling, heat transfer, rotary kiln, clinker, flame simulation*

1. Introduction

Clinker burning still remains a very complex process in terms of chemical and thermal processes occurring within the clinkering plant. Thus modeling such a process entails a very complex calculation and requires the use of some simplifications.

For this study it was considered only the clinkering area, which is a part of the rotary kiln. The clinkering area of the rotary kiln is divided (in length) on segments (spatial increments). On each segment a quantity of fuel is burned. Respectively, these quantities are correlated, in our view, with the shape of the flame and the burning behavior of the fuel that represents a key element to decide the productivity of the plant, the quality of the clinker and amount and concentration of exhaust gases. The way in which the total amount of fuel is distributed over each segment determines the gas temperature profile and, also, the highest value of temperature and its position in the flame.

Temperature profile must be carefully controlled and maintained to avoid large fluctuations that could affect clinker quality and coating stability. Moreover, in present, fossil fuels are replaced on an increasing scale with alternative fuels. The last ones could exhibit unsteady burning behavior easier than fossil fuels, making more difficult to control the shape and temperature of the flame. Consequently, the necessity to gain an insight of the process before it actually happens becomes obvious, leading to cost and time savings.

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A series of efforts were already made by both academic world and cement industry, in order to model rotary kilns as concerning flame and heat transfer within the kiln.

According to the literature the issues of fuel distribution along the axis of the flame is rather little explored. In [1] flame temperature has been correlated with the amount of fuel injected to estimate coating thickness by measuring some of the process parameters. Temperature profile of the gas throughout the kiln was simulated by means of Computational Fluid Dynamics (CFD) methods by using series of simplifications [2]. A study of kiln outer shell temperature was made in [3] by relating to several proposed gas temperature curves within the entire kiln. Also CFD computations were performed in [4] with the aim of studying the effect of burner modification and the combustion air velocity. The closer approach to ours, can be found in [5], were each segment of the kiln received a certain amount of fuel.

2. Mathematical model

2.1. General issues

A series of limitations and simplifications were included in the model mainly because very little information regarding what happens inside the *whole* rotary kiln is available (for obvious reasons). We considered in this work the rotary kiln used in a dry process clinkering plant. The length of the rotary kiln was 40m, while the flame length was adopted to be 15 m.

We also used the following simplifications:

- gas recirculation was neglected;
- gas temperature was constant throughout each segment and on the transversal section of the rotary kiln;
- the filling degree with material was set constant over all segments;
- flame length and the overall amount of fuel burnt were set [5];
- temperature profile of the material over the modeled area was adopted from literature [5];
- dust transport and settlement were neglected;
- exo/endothermal effects [6] were evenly distributed over the length of the burning zone.

2.2. Description of the mathematical model

The burning (clinkering)/flame area is indicated in Figure 1. This area was split in 15 equal length segments (1m each) as could be observed in Figure 2. Each segment constitutes a cell in which thermal balance was performed.

As inputs were considered: the sensible heat carried by gas exiting the preceding segment (Q_{g_in}), by material coming from the next segment (Q_{m_in}), heat generated (Q_c, Q_f) in the segment, while the outputs were: the sensible heat of the gas exiting the current segment (Q_{g_out}), material (Q_{m_out}), heat lost through the walls (Q_p).

Following this line of reasoning, output parameters (such as temperature, gas volumes etc.) from a segment will become input parameters for the next segment. All thermal effects (endo/exo) were included in the heat of reaction corresponding *only* to the clinkering area (Q_f), that was evenly distributed over the rotary kiln. Q_c - represents the amount of heat generated by the amount of fuel burnt on each segment.

Complex heat transfer phenomena could be observed on each segment (Figure 3). Gas has the highest temperature, therefore heat is transferred from gas to wall (Q_{gp}), and to the material (Q_{gm}); also, heat is transferred from the wall to the material by radiation or, directly, by conduction. (Another part of the incoming heat

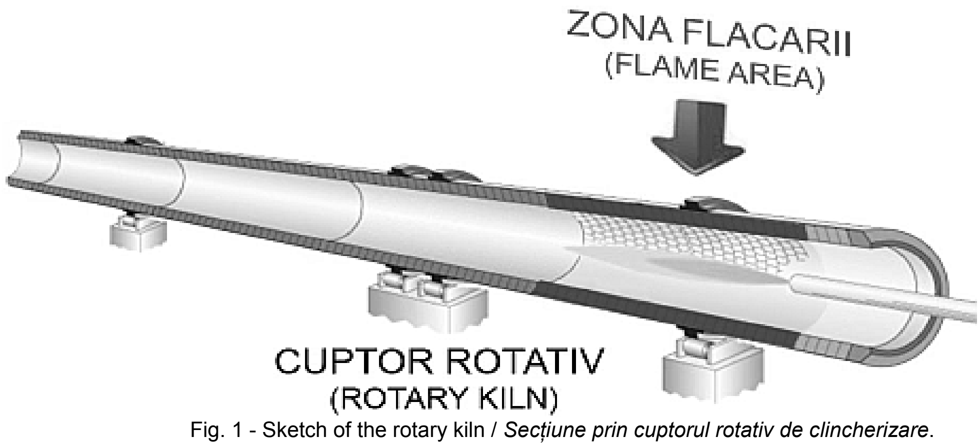

Fig. 1 - Sketch of the rotary kiln / *Secțiune prin cuptorul rotativ de clincherizare*.

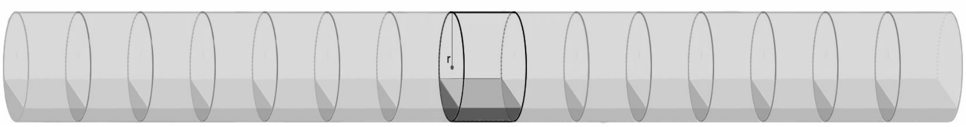

Fig. 2 - Flame area partition in segments / *Împărțirea zonei flăcării pe segmente.*

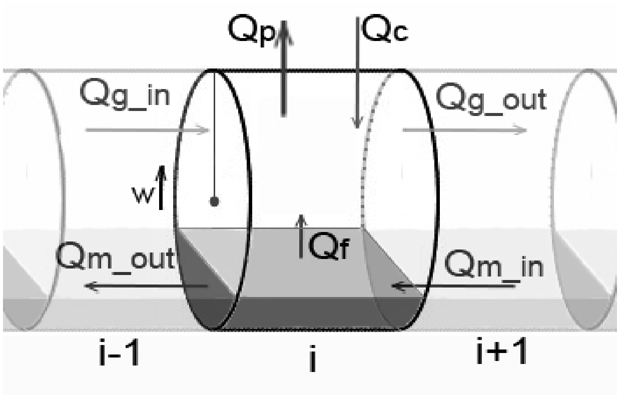

Fig. 3 - Heat transfer within the "i^{th}" segment / *Transferul termic corespunzător segmentului "i".*

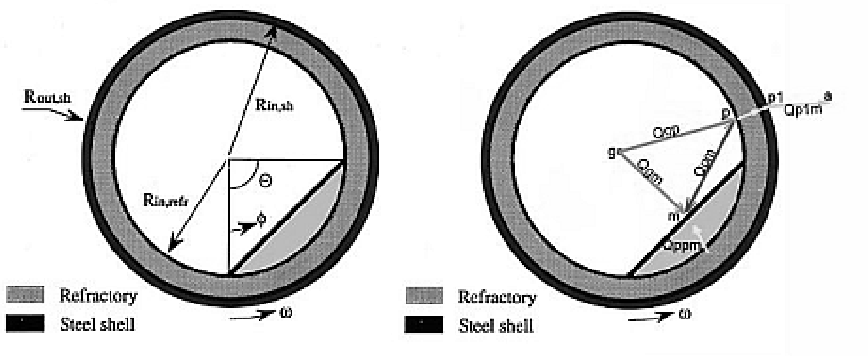

Fig. 4 - Thermal balance in the "i^{th}" segment [2] / *Bilanțul termic realizat pe segmentul "i".*

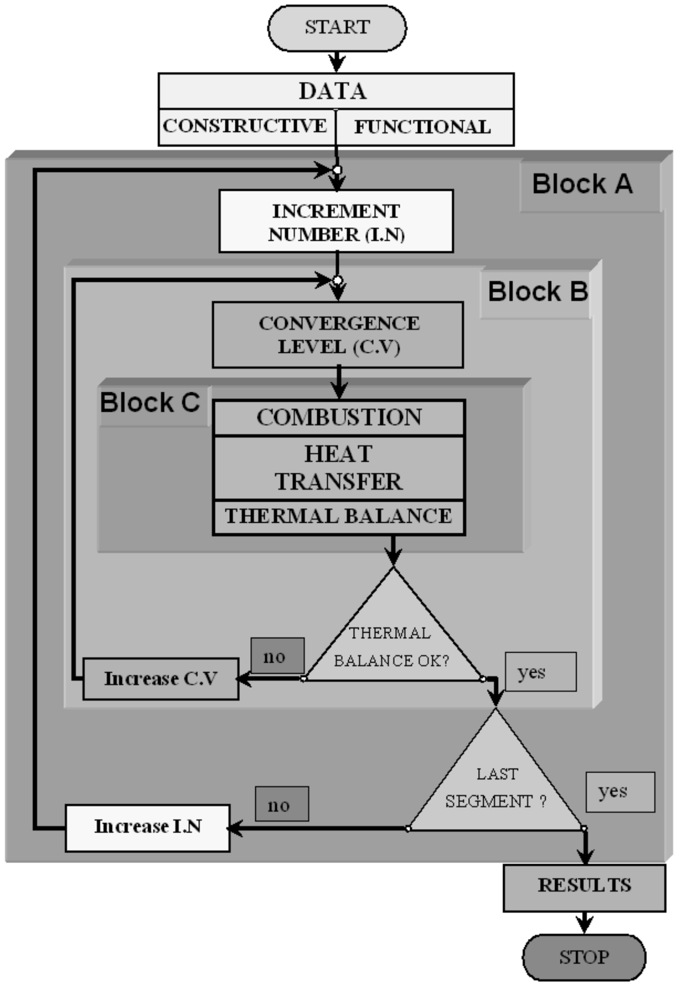

Fig. 5 - Workflow chart / *Schema logică a modelului matematic.*

towards the wall is lost to the environment – see Fig. 4). An exception to this temperature hierarchy can be identified in the part of the kiln that contains the burner and in the initial part of the flame, where the material has the highest temperature, followed by the walls and then the gas (the opposite case).

Basically all types of heat transfer mechanism (radiation, convection, conduction) contribute to the overall heat transfer. However, as the gas temperature is the highest in this area, and, also, its values are high enough, the prevailing mechanism is the radiative one.

In Figure 5 it was given the workflow of the model.

The main part of the model containing equations for computing combustion, heat transfer, and thermal balance can be found in *Block C*. All this calculations in *Block C* are made over each segment. However, calculations are made numerically; as a consequence, convergence of the inputs and outputs will be reached following several iterations. The unknown parameters giving the gas and, respectively, wall temperatures, together with the corresponding heat loss to the environment are calculated. This constitutes *Block B*. All this calculations will be performed over all segments (*Block A*).

Input data is made of constructive and functional parameters (size of the kiln, burning zone length, data concerning refractory lining, temperature, mass and gas flows etc.). Equations of the model dealing with heat transfer are the classical ones used in thermal balance equations and could be found in [6]. Gas composition changes at the exit of each segment due to the amount of fuel burnt therefore it is also computed iteratively. The fuel used was gas (containing 95% methane).

Due to the amount of calculation required, it was developed a computer application in PHP language.

2.3. Assumed parameters

In this work several distributions of fuel over each segment were assumed (Fig. 6).

In Figure 6, a number of six distributions of fuel for the clinkering area are represented: some linear, others nonlinear. According to the curve c3, the fuel is distributed with a constant value throughout the clinkering area; in the c1, c2 cases, the biggest amount of fuel is burnt in the first part, while in case c2, c5 the situation is opposite. The case c4 represent a symmetric allocation of the fuel over the clinkering area.

In the clinkering process, a coating layer is created on the inner surface of the refractory lining. This layer brings some advantages: it limits the heat lost, it protects the refractory lining, and as a consequence, it increases the interval of time between major maintenance efforts. In order to maintain optimal temperature regime to obtain stable and uniform coating, it is mandatory to monitor and control a large number of parameters (such as: pressure drop over the clinkering plant, outer kiln shell cooling etc).

In this paper we used some cases of distribution of the coating width over the clinkering area (seven cases). In the first case (c0) there is no coating at all (it could be used for comparison reasons). The second (c1) and the fifth (c4) represent constant width of the coating (0,1m, 0,2m respectively). On the other hand, cases c2, c3, c6 represent a variation of the coating on the clinkering area of the rotary kiln.

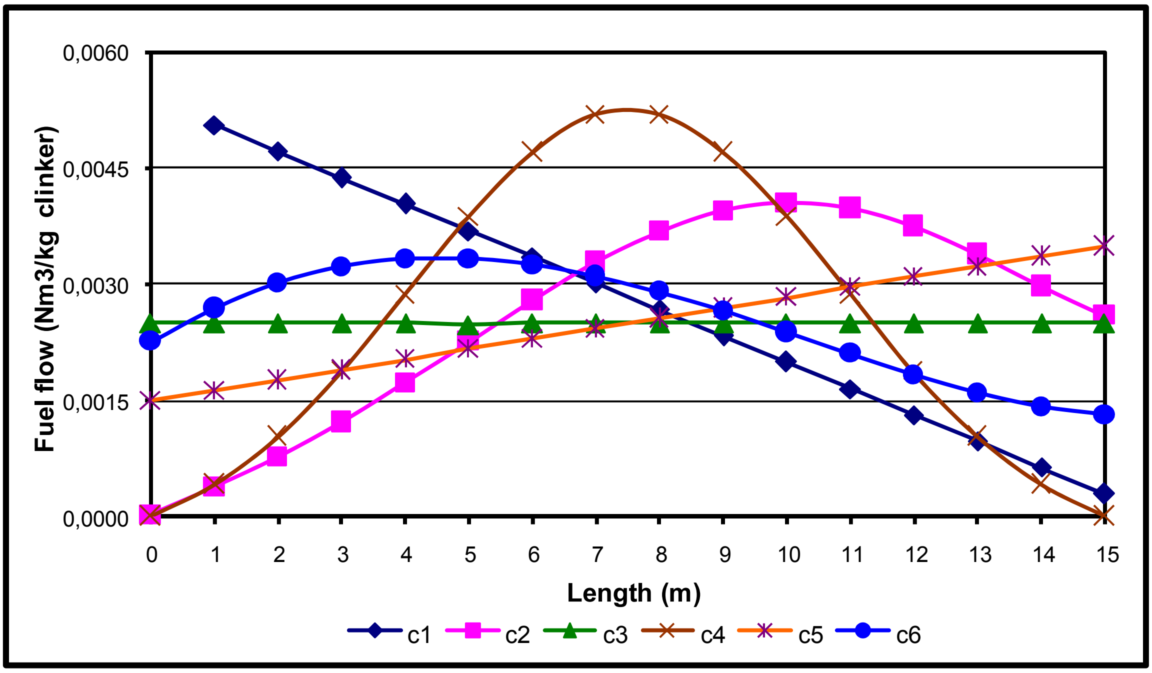

Fig. 6 - The distribution of the fuel over the clinkering area / *Distribuția combustibilului în zona de clincherizare.*

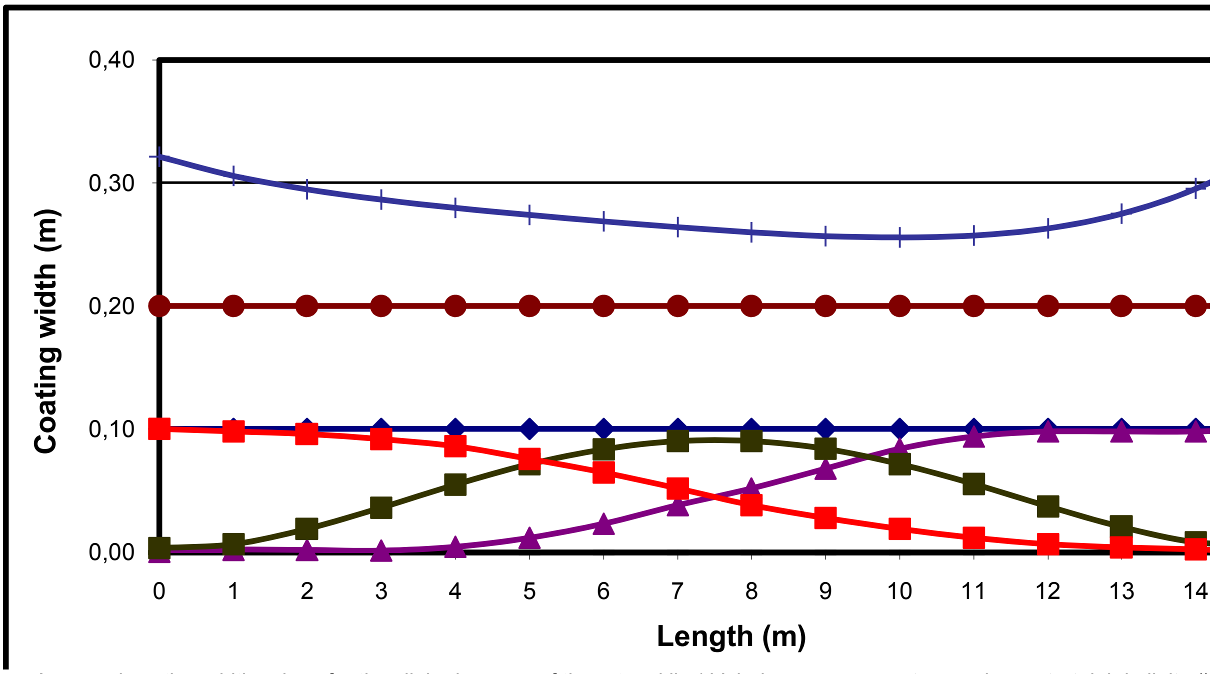

Fig. 7 - Assumed coating width values for the clinkering area of the rotary kiln / *Valori presupuse pentru grosimea stratului de lipitură în zona de clincherizare.*

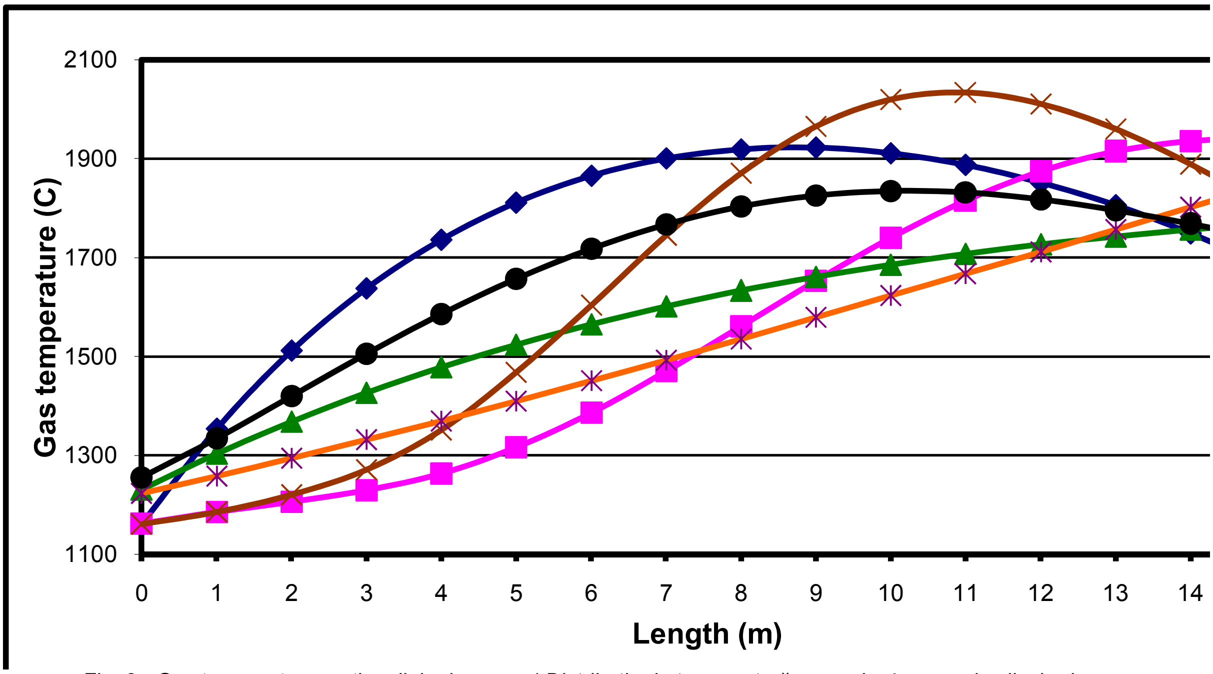

Fig. 8 - Gas temperature on the clinkering area / *Distribuţia de temperatură a gazelor în zona de clincherizare.*

3. Results and discussion

An application was developed based on the mathematical model sketched in Figure 5. Various fuel distributions given in Figure 6 where used in computations: results were given in Figures 8, 9 in which there were represented the temperature profiles of the gas and the outer kiln shell.

The highest temperature observed is provided by the case C4 (the gaussian distribution). In this case at the top of the flame it was recorded a temperature of 2034°C.

Figure 9 shows that the coating width is an important parameter influencing the amount of heat lost through the walls. It was found that when the coating width changed from 0 to 0.2 m and then to 0.3 m the maximum temperature of the kiln shell dropped from 430 (no coating case) to 334, and then 278 respectively.

3.1. Case studies

In order to compare our model results we used data from literature as follows.

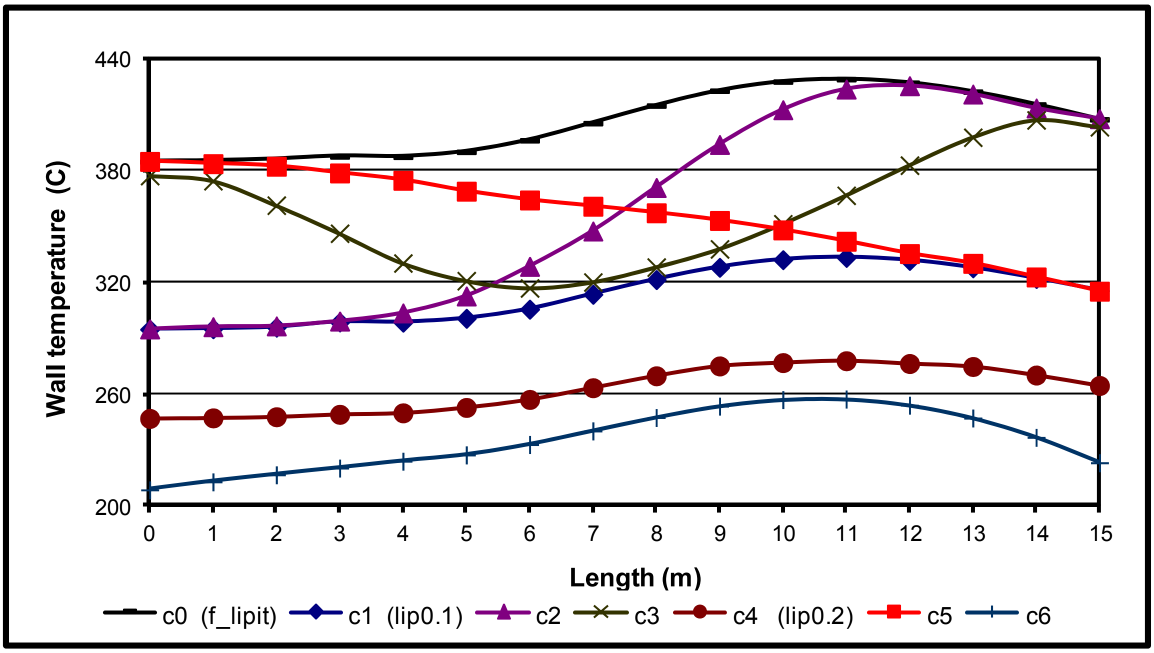

Fig. 9 - The external wall temperature for c4 fuel distribution and for various coating width values / *Temperatura exterioară a peretelui pentru distribuția de combustibil c4 şi diferite grosimi ale stratului de lipitură.*

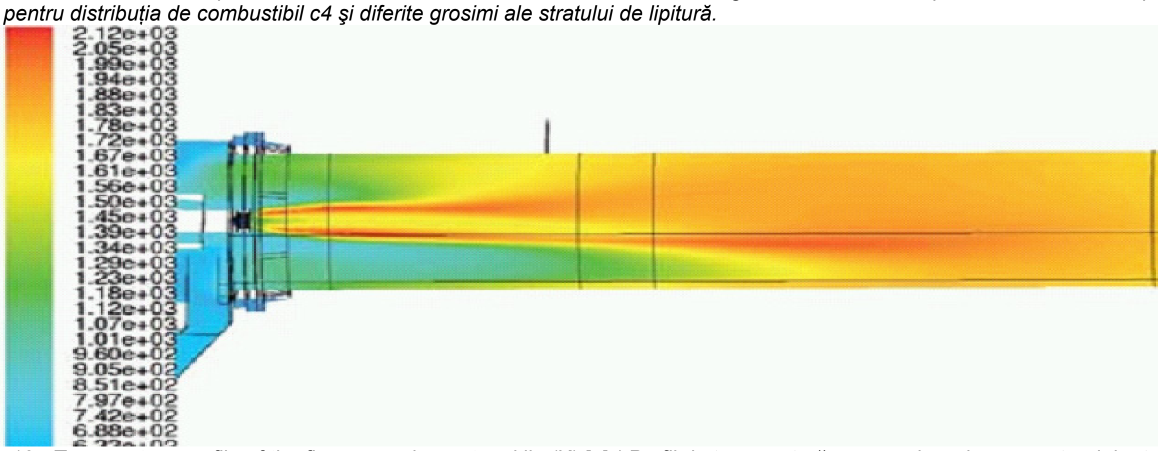

Fig. 10 - Temperature profile of the flame area in a rotary kiln (K) [4] / *Profil de temperatură în zona de ardere a cuptorului rotativ.*

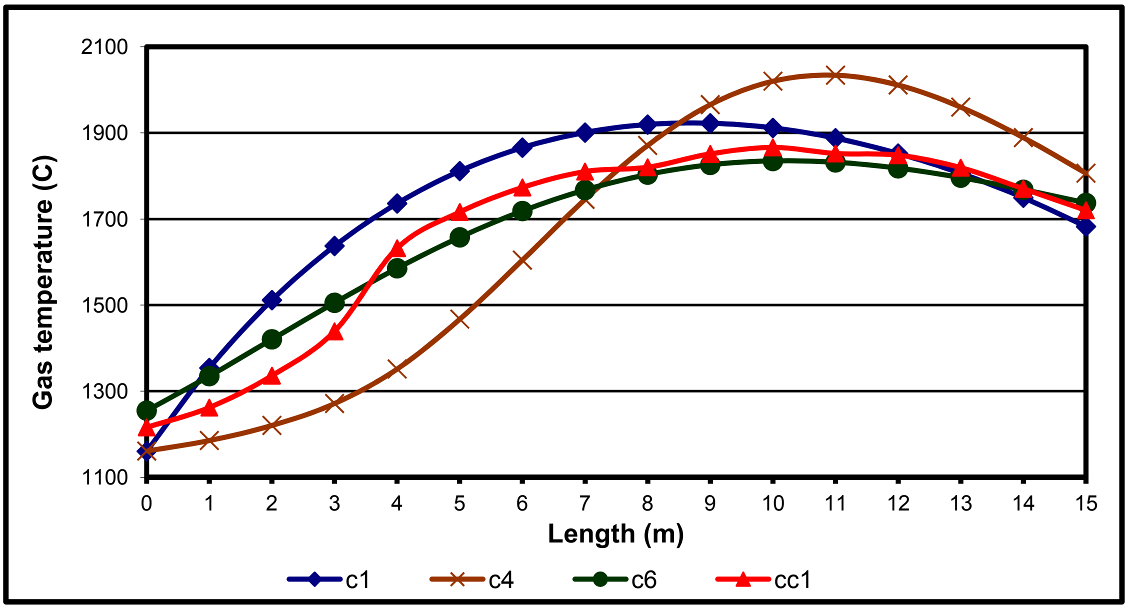

Fig. 11 - Temperature profile (cc1) from literature, corresponding to data from figure 10, in comparison with c1, c4, c6 fuel distributions from Figure 8 / *Distribuția de temperatură (cc1) corespunzătoare datelor din figura 10, în comparație cu distribuțiile c1, c4 şi c6 din figura 8.*

Case a)

In [4] we found the results of a CFD (Computational fluid dynamics) simulation, given in Figure 10. We digitally analyzed the temperature profile over the simulation area, which corresponds to the length and diameter of our computations. A comparison was made with the averaged temperatures obtained from figure 10 (resulting the curve cc1 in Figure 11) and our simulation results. It could be easily observed that curve cc1 is very close to curve c6 (a non-linear distribution of fuel) with the highest amount of fuel burnt in the first half of the clinkering area.

Case b)

Compared to case a) given in Figure 12, [2], the temperature profile in the flame is symmetrical. In this case (which is not as realistic as compared to the previous one) the temperature profile, averaged from meter to meter, is not as close to c6 distribution, however curves cc2, and c6 are not very remote at least at the beginning and at the end (Fig. 13). On the other side in the second part of the flame, curve cc2 and curve c1 are very close and follow the same trend. As concerning the general trend, even they do not have quite similar values, curve cc2 could be viewed as a combination of the other ones.

As there is no possibility to measure temperature profiles over the overall length of the clinkering area, the most reliable indicator about what happens inside the kiln is the thermal imaging. The map is obtained by using an external temperature scanner that provides very accurate measurements of the kiln shell temperature. In Figure 14, it is shown such a real life temperature map.

The area of interest for us starts from the second meter. The dark rectangle positioned around the fourth meter (Figure 14), suggesting a temperature drop, is due to the existence of the external support ring attached to the rotary kiln (that lays on the roles).

We made the simulation of the kiln shell temperature. Figure 15 was made by selecting the

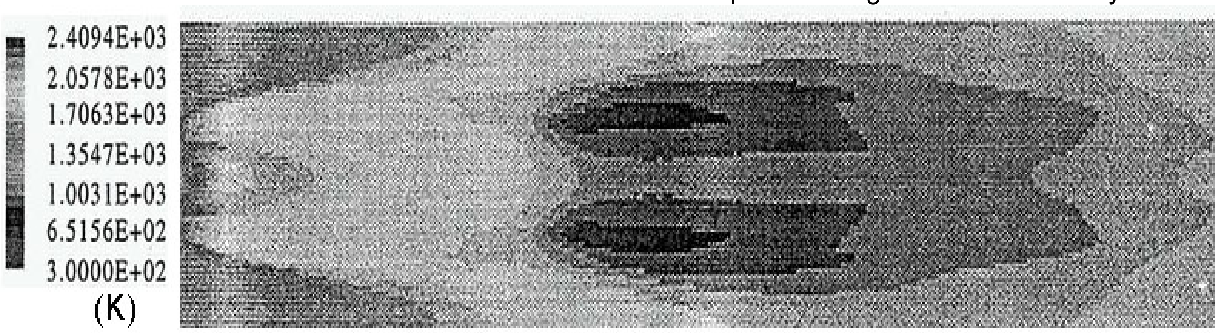

Fig. 12 - Gas temperature distribution (K) [2] / *Distribuția de temperatură.*

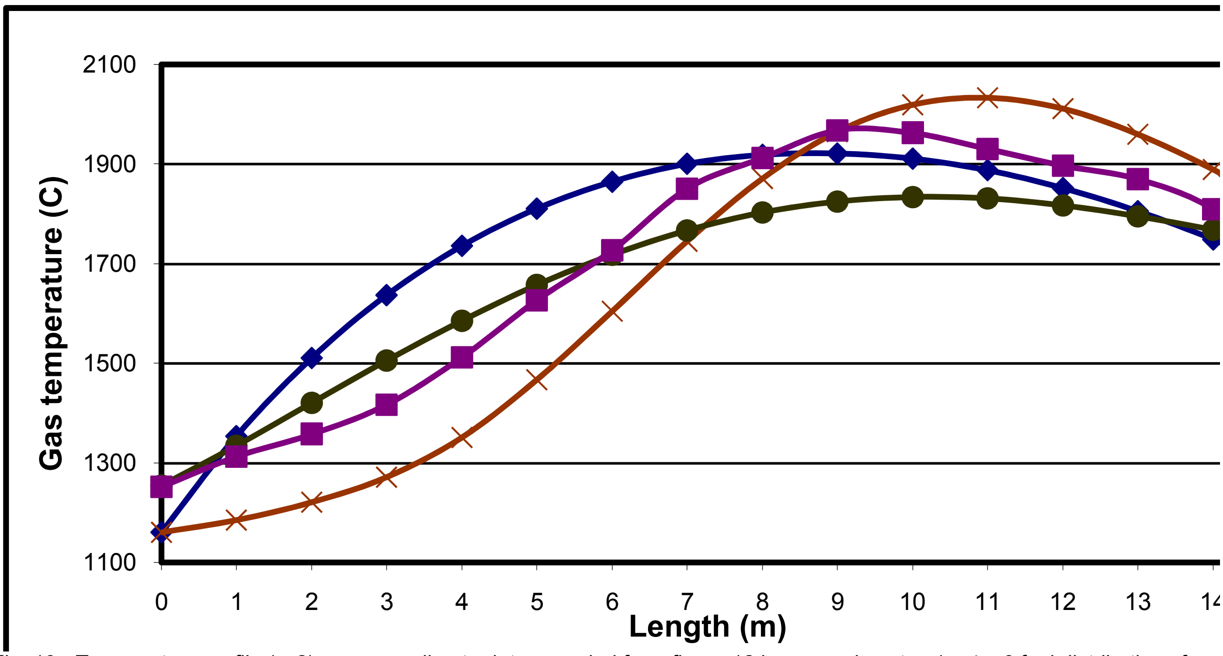

Fig. 13 - Temperature profile (cc2) corresponding to data recorded from figure 12 in comparison to c1, c4, c6 fuel distributions from Figure 8 / *Profilul de termperatură (cc2) corespunzător figurii 12 în comparație cu cel corespunzător distribuțiilor c1, c4, c6.*

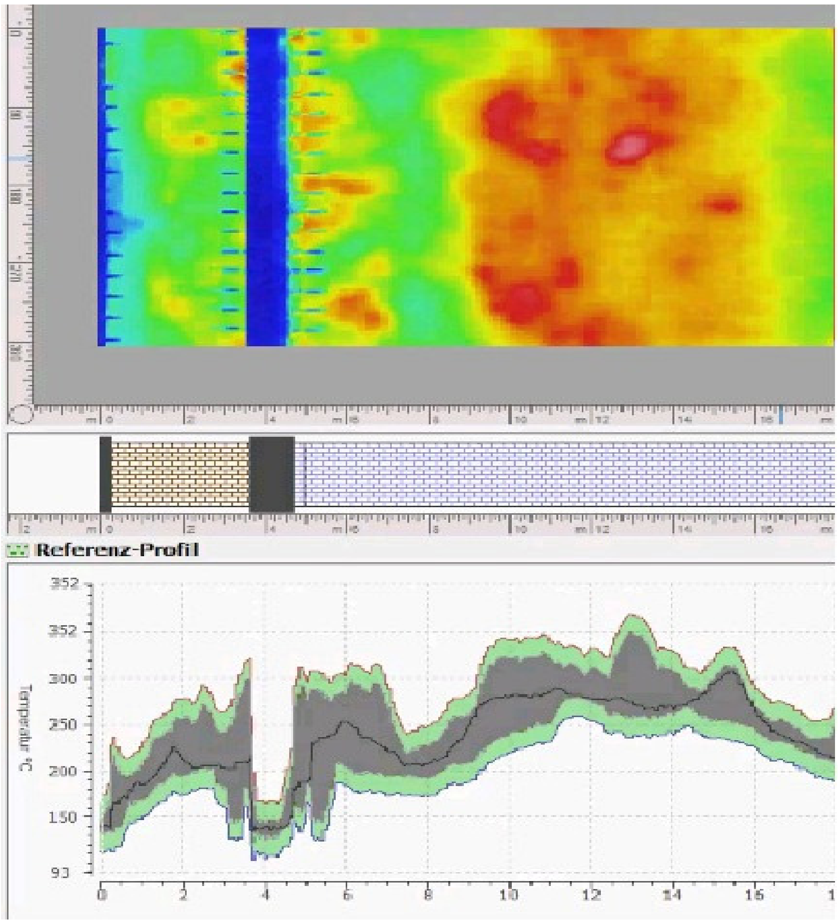

Fig. 14 - Thermal image of the rotary kiln outer shell (real life, industrial kiln outer shell burning zone temperature profile) / *Imagine (harta) termică reală a suprafeței exterioare a cuptorului în zona de interes.*

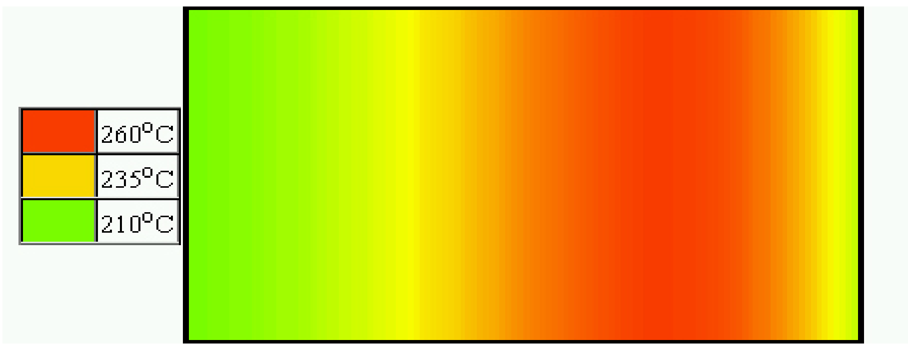

Fig. 15 - Thermal image of the rotary kiln outer shell from simulation according with case c4 (gaussian distribution of fuel in Figure 6) and coating width c6 from Figure 9 / *Imagine (harta) termică, calculată, a zonei de interes, corespunzătoare distribuției gaussiene de combustibil (fig. 6) şi grosimii stratului de lipitură c6 din figura 9.*

closest fuel distribution which is c1 and by adjusting the coating width. It is worth to be mentioned that real life data show local variations in temperature, which is not always uniform over the circumference of the kiln. This could be attributed to variations in coating width and, also, by possible, localized lining wear. These exceptions could be easily observed in Figure 14 as hot spots, for example at around 6 meters, but not only (at 15 meters there are some other isolated spots).

4. Conclusions

Simulations made in that paper showed a good accuracy as compared to the results coming from the literature. From that reason we consider - even if the model is not perfect and there are still some limitations that we a still have to deal with - that this model can be used for optimization purposes. According to the type of fuel used (i.e. low calorific value, volatile contents etc) one can physically shape the flame by adjusting the burner (an expensive solution) or can simplify this issue by simulating the temperature of the flame). A further refinement of the model will consider only the material temperature profile while the amount of fuel to be burnt at each position will result from computations.

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MANIFESTĂRI ŞTIINȚIFICE / SCIENTIFIC EVENTS

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The aim of this meeting is to offer an update of recent innovations in both fundamental and applied aspects and to highlight the latest advances and progress in the field of inorganic nanomaterials (inorganics, ceramics, hybrids and bio-inspired materials).

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♦ **Nanomaterials, functional porous materials, coordination networks, bio-inspired nanomaterials, hybrid nanomaterials and living materials:** Nanostructures, nanoparticles, nanotubes, ceramics, membranes, films, self-assembly, supramolecular systems, co-ordination polymers, zeolites, MOFs, mesoporous materials, hierarchically structured materials, carbons, natural materials, bioinspired and biomimetic materials, biomineralisation and biotemplating, bio-integrated materials, biocomposites, organometalics, green materials for construction, inorganic switches etc.

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