REALIZAREA BILANȚURILOR TERMICE ALE UNEI INSTALAȚII DE CLINCHERIZARE PE DIFERITE PERIOADE DE TIMP▲
HEAT BALANCE COMPUTATION ON A CLINKERING PLANT OVER DIFFERENT TIME STEPS

ZENO GHIZDĂVEȚ*, ROMAN GRĂDINARU
Universitatea POLITEHNICA Bucureşti, Str. G. Polizu nr. 1, S1, 011061, Bucureşti, România

In this paper, heat balance calculations were performed on a clinkering plant based on the dry process, no calciner. Parameter values were iteratively averaged over different time periods. The purpose of this work is to determine the influence of the averaging time interval on the precision and accuracy of the calculations and to extract some useful information about the process itself.

Five parameters that were selected by a simple statistical correlation analysis were considered. For each parameter two series of data of the same length (256 hours) of uninterrupted processing were used. Ordinary variations for the process parameters' evolution and for the particular plant were recorded.

Fractal dimension calculations were made on each parameter, for both hourly and averaged sequences of data and for the two series (this has been done for confirmation). Results clearly show that each parameter can be identified by a particular fractal dimension. This simple technique can be used, for instance, to detect abnormal trends that can escape visual analysis.

In acest articol au fost realizate bilanțuri termice pe o instalație de clincherizare bazată pe procedeul uscat, fără calcinator. Valorile parametrilor de proces considerați au fost mediate, iterativ, pe diferite perioade de timp. Scopul a fost acela de a determina influența perioadei de timp pe care se face medierea asupra preciziei calculelor dar şi de a extrage o serie de informații utile despre procesul de clincherizare.

Au fost selectați cinci parametri de proces folosind o simplă analiză statistică de corelație. Pentru fiecare parametru de proces au fost folosite două serii de date în care au fost înregistrate valori pe parcursul a 256 ore de funcționare neîntreruptă a instalației de clincherizare. Evoluțiile tuturor acestor parametri de proces au înregistat numai variații uzuale pentru această fabrică de ciment.

Pentru fiecare parametru a fost obținută dimensiunea fractală, atât pentru valorile orare cât şi pentru cele mediate, pentru ambele serii de date, pentru confirmare. Rezultatele au arătat că fiecare parametru poate fi identificat în mod clar printr-o valoare specifică a dimensiunii fractale. Această metodă simplă poate fi utilizată, spre exemplu, pentru a identifica evoluții anormale care pot să scape analizei vizuale uzuale.

***Keywords:** clinkering plant, heat balance, fractal dimension*

1. Introduction

Among all equipment involved in obtaining clinker, the highest amount of the heat required goes to the clinkering plant.[1] Therefore both researchers and process engineers paid a lot of attention, over time, to this plant with the aim to reduce fuel consumption while maximizing clinker output, for a quality product. One instrument that can be used in the purpose is to employ heat balance calculations.

Heat balances are used in the examination of the various stages of a process, over the whole process and even extending over the all production system from the raw materials to the finished product.

The cement industry is a heat intensive industry and the increasing cost of fuel has caused the industries to examine means of reducing heat consumption in processing. In this way heat balances could be useful.

Heat and mass balance are still one of the important tools to evaluate, diagnose and optimize the clinkering plant [1]. By them, mass and heat balance can help to identify the particular aspect where improvements could and must be made, especially when targeting the outputs' performance of the plant and also heat and energy consumption correlation to laboratory test. Heat balances could help to improve clinker quality. Also they are useful when new raw materials, fuels and process control strategies are introduced. As a rule of thumb, the higher the fluctuations of the process parameters are - the more the heat balance calculations are becoming necessary but, on the other hand, more difficult to produce. This last statement can be supported by the following assertions, regarding the problems that can be identified when computing the heat balance:

- False air inlet: this amount of air cannot be

* Autor corespondent/*Corresponding author*,
Tel.: +40214023874, e-mail: zghizdavet@gmail.com

▲ Lucrare prezentată la / *Paper presented at:* Consilox XI

measured though it can be computed from the gas analysis.

- Cooling air temperature fluctuations are not always accounted for, accurately, yet play a certain role in heat balances [2].

- Fuel features, such as low calorific value, moisture content, chemical composition etc. are not always constant.

- Raw meal composition and grain size distribution are not always constant, which can induce differences in their burnability.

- Materials' transport and transformation in the plant requires in excess of tens of minutes while gas needs considerably less to pass through the plant (at least of an order of magnitude). Thus, a time lag between the two streams arise, which disconnects measurements of the opposite parts of the clinkering plant for the solid and gaseous phases that circulate, generally speaking (for the most of the plant), in counter-current.

- Process control strategy, which is, generally speaking, set for a given plant, can be altered by the influence of the operators.

In order to reduce the imprecision of the heat balance due to the above mentioned factors a solution could be the calculation over larger time intervals.

In this paper it was studied the influence of the time interval over the accuracy of the results.

The targeted clinkering plant is composed by: preheater, rotary kiln, grate cooler. The highest amount of fuel is used in the rotary kiln but also a part of the fuel is burned in kiln rising duct.

2. Input data

Two series of data concerning process parameters registered over a period of 256 hours were used in thermal balance calculations for a dry process clinkering plant. The aim was to compute heat specific consumption.

Table 1a

Partial correlation coefficients for the input parameters (series S1) / *Coeficienţii parţiali de corelaţie pentru mărimile de intrare (seria S1)*

	t_sc	d_cl	t_cl	t_ae	d_cc
t_sc		-0.9638	-0.9179	-0.9512	0.9585
d_cl			-0.9641	-0.9943	0.9986
t_cl				-0.9529	0.9647
t_ae					0.9966

Table 1b

Partial correlation coefficients for the input parameters (series S2) / *Coeficienţii parţiali de corelaţie pentru mărimile de intrare (seria S2).*

	t_sc	d_cl	t_cl	t_ae	d_cc
t_sc		-0.9461	-0.903	-0.9363	0.9398
d_cl			-0.9607	-0.9932	0.9986
t_cl				-0.9495	0.9611
t_ae					0.9955

Remarks:

Partial Correlation coefficients measure the strength of the relationship between each pair of variables having already accounted for the relationships with the other variables (definition given in Centurion Statgraphics manual; Centurion Statgraphics analysis software has been used for the computation of these coefficients).

t_sc - gas temperature of the exit of preheater [ºC];
t_cl - clinker temperature [ºC];
t_ae - temperature of the excess air [ºC];
d_cl - clinker flow [t/h];
d_cc - fuel flow that will be further computed [t/h].

The input parameters were analyzed by means of a simple statistical analysis test. Table 1, a and b, give the value of the partial correlation coefficients that has statistical significance (all other monitored parameters, such as kiln speed, NO_x level etc. - that are not involved in the heat balance - show very low partial correlation coefficients). In this way, a confirmation of the link existing between heat balance parameters was made.

Input data that correspond to the studied series are represented in figures 2-5. We used two series of data, *S1* and *S2*, equally sized (256 samples), constantly registered (no process stops), from two different time intervals but coming from the same cement plant. All input data were averaged over the amount of time elapsed. As it can be seen, the productivity of the clinker plant was variable on the given period of time.

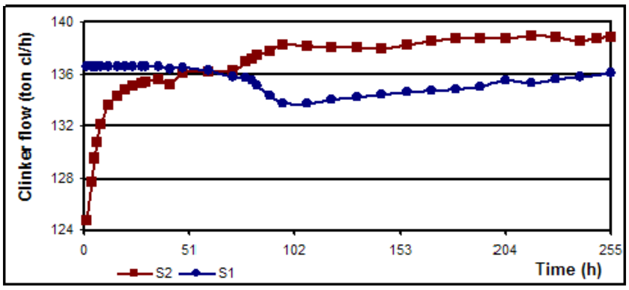


Fig. 1 - Clinker flow averaged over different time steps (S1 and S2 series). *Debitul de clincher mediat pe diferite intervale de timp (seriile S1 şi S2).*

In Figure 1 is represented the averaged clinker flow over different time steps for the studied series. It is possible that the two trends reflect different strategies employed over time (these ones can be identified also in the following figures) that can be supported by arguments only by the means of a further, thorough approach [2, 3].

For charts in Figures 1-5 and 7, as it was expected, one can draw the conclusion that the influence of a fluctuation from the previous value is more important in early times and progressively decreases with averaging time. A peak thus results from the existence and the succession of two opposing, monotonic sequences (or, at least, predominant) over a time interval and important courses of evolution (trends). In this manner both the link between process parameters (qualitative) and the amount of variation of their values can be identified much easier than in a highly irregular, hourly recorded parameter evolution. This is due to the smooth nature of the resulting curve which can be easier to be read and analyzed (compared to an irregular, saw-like, ordinary recorded signal). However, this type of representation *alone* should be avoided, providing a partial view of the problem to be analyzed and has to be correlated with proper techniques for analysis and so forth.

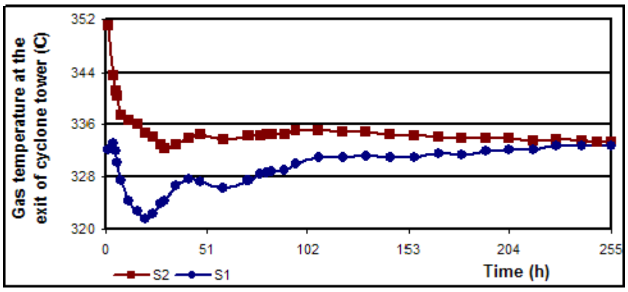


Fig. 2 - Gas temperature averaged over different time steps / *Temperatura gazelor evacuate din schimbătorul de căldură, mediată pe diferite intervale de timp.*

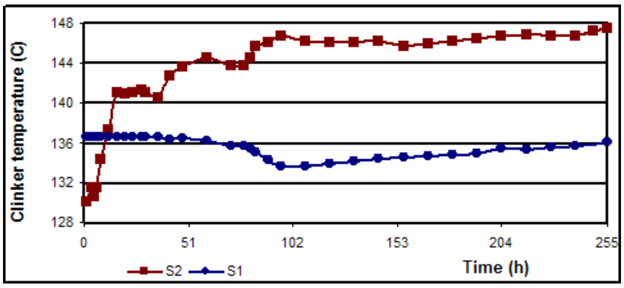


Fig. 3 - Clinker temperature averaged over different time steps / *Temperatura clincherului, mediată pe diferite intervale de timp.*

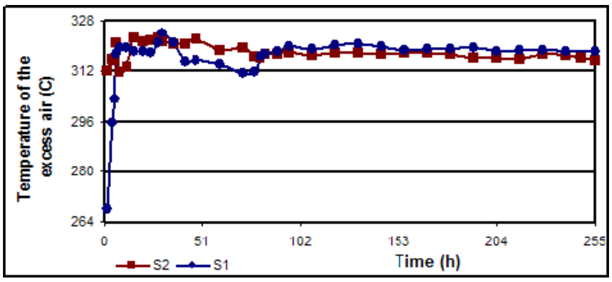


Fig. 4 - Excess air temperature averaged over different time steps / *Temperatura aerului în exces, mediată pe diferite intervale de timp.*

3. Results and discussions

From our computation the first result will be heat consumption (kJ/kg clinker). From this result we will derive the equivalent fuel flow (t/h) by introducing the clinker flow (t/h) represented in Figure 2. Correlations can be easily drawn by comparing the shape of the curves. For example, averaged clinker flow (Fig. 1) and clinker temperature (Fig. 3) for *series S1* are very similar. For the *series S2*, averaged clinker flow and clinker temperature are very similar in their evolution; they all present an opposite but correlated behavior as compared to gas temperature (Fig. 2), which is also observed in the statistical analysis given in Table 1 (correlation coefficients are high *and* negative).

A still unknown value that is highly important in the economy of the heat balance is the heat of reaction. This accounts for more then 50% (Fig. 6); in the paper it was computed. This heat of reaction - that is related to many factors - could be seen for the future as a research field for further reducing the heat consumption when all other amounts of heat outputs where already minimized.

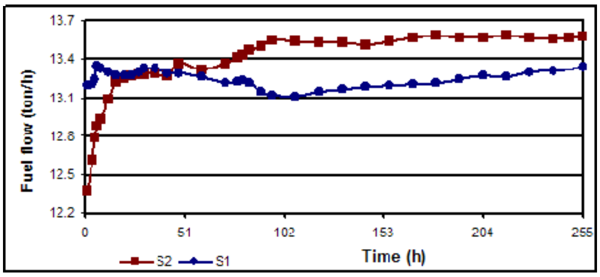


Fig. 5 - Fuel flow averaged over different time steps / *Debitul de combustibil mediat pe diferite intervale de timp.*

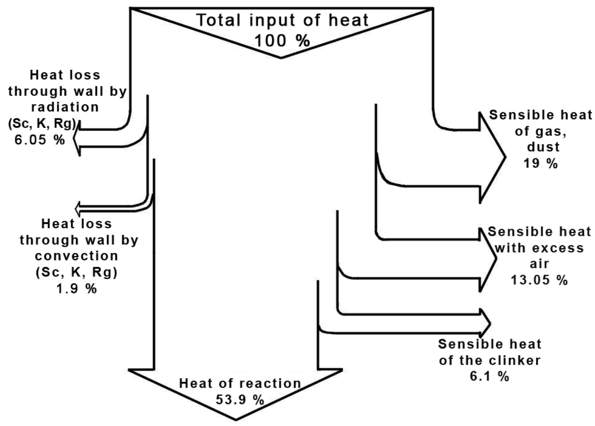


Fig. 6 - A detailed picture of the heat outputs, averaged over 12 hours (*S2* series) / *Căldurile ieşite, mediate pe un interval de 12 ore (seria S2).*

The clinkering plant used for firing two kinds of fuel: coal, the main part, and petcoke, in a smaller amount. By knowing their low calorific value, it was computed the equivalent fuel flow which would represent the real fuel consumption only if the fuels' properties remained constant. This equivalent fuel flow was represented against the computed one, this time being not averaged (meaning, registered hourly values) showing improving accuracy over time (to the extent that the trends become very close) for *series S1* (Fig. 8).

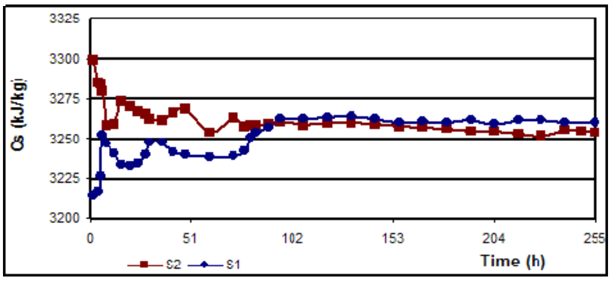


Fig. 7 - Specific computed heat consumption averaged over different time steps / *Consumul specific de căldură (calculat) mediat pe diferite intervale de timp.*

In *series S2* case (Fig. 9), even that at some time intervals the trends could be viewed as being similar, it can be identified a gap that persists over the averaging time. In both cases, exceptions (outliers, values far away from the general trend and from the previous and next samples from the same evolution and from the computed fuel flows) can be identified. No technological explanation can be provided to this point for these exceptional values; they should be further confirmed as *outliers* by using other methods [3, 4].

To better understand the benefits of the process of smoothing evolutions, as we did so far by using averaged values of the process parameters, we give only two examples in Figure 10 a-d: the time series of two parameters i.e. *Gas temperature at the exit of preheater* and *Temperature of the excess air*, comparatively for the two series, *S1* and *S2*. Values are non-dimensional. This allows, generally speaking, for a comparison when the order of magnitude and/or units for various parameters are different.

Several remarks can be drawn from the visual inspection of these series:

- there is a strong irregular behavior in all plots which make their analysis difficult;
- patterns may or may not be identified over different time intervals but sudden changes can occur; this observation makes pattern recognition mostly a tool for a better understanding of the process rather than an operative one;
- some of the parameters do exhibit trends but others do not; therefore it is difficult to correlate them all by investigating this approach;

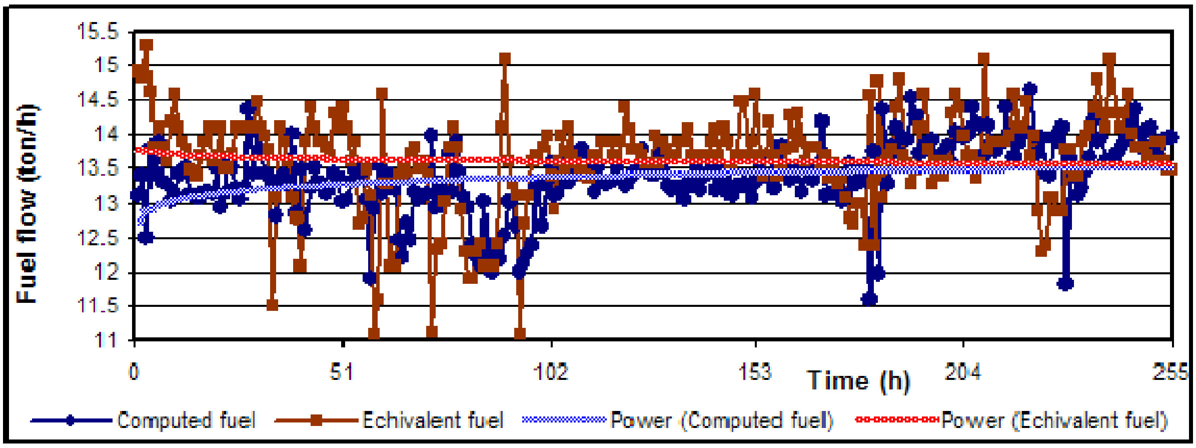


Fig. 8 - Computed and equivalent fuel flow (*series S1*) / *Debitul de combustibil calculat şi echivalent (seria S1).*

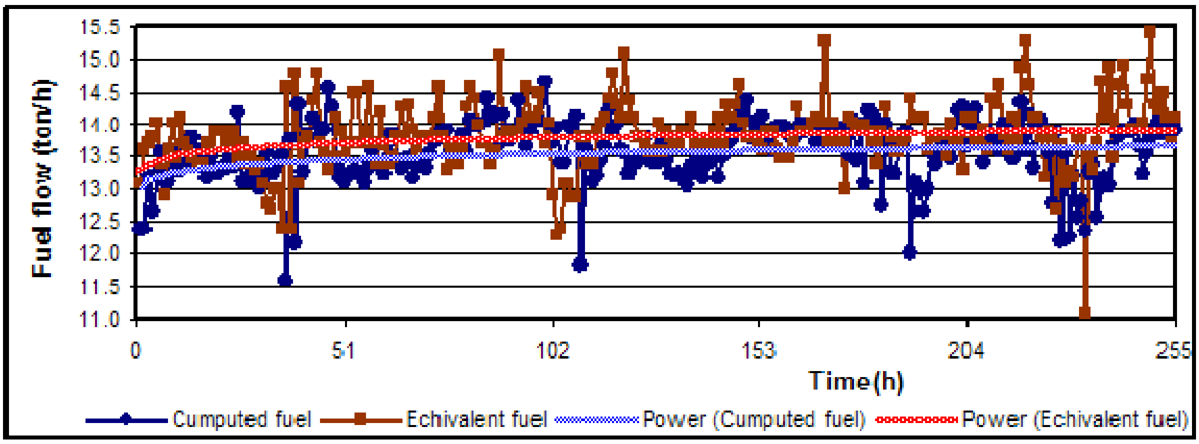
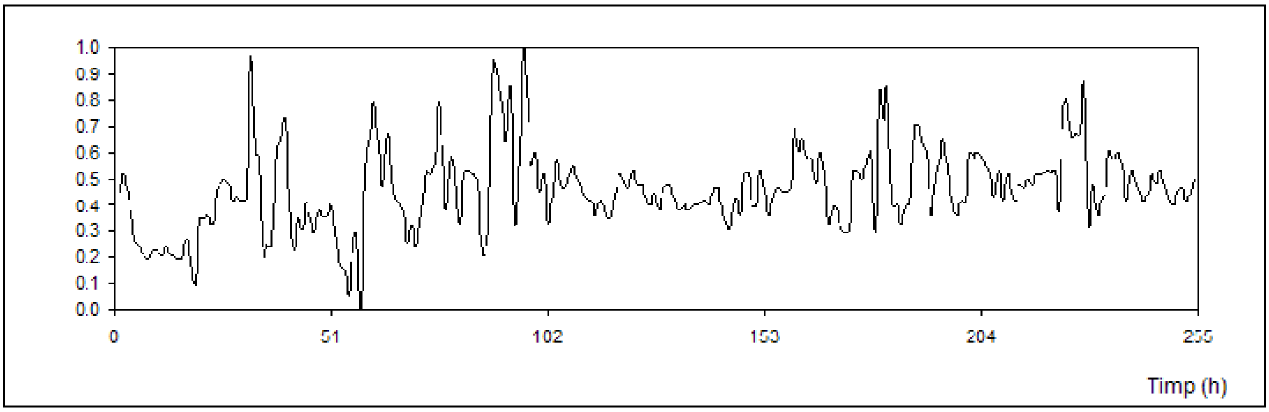
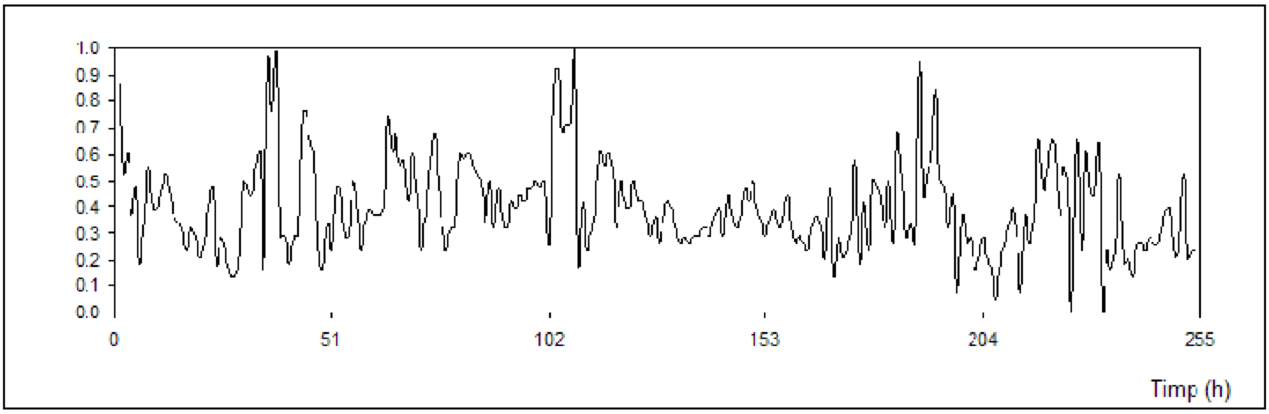


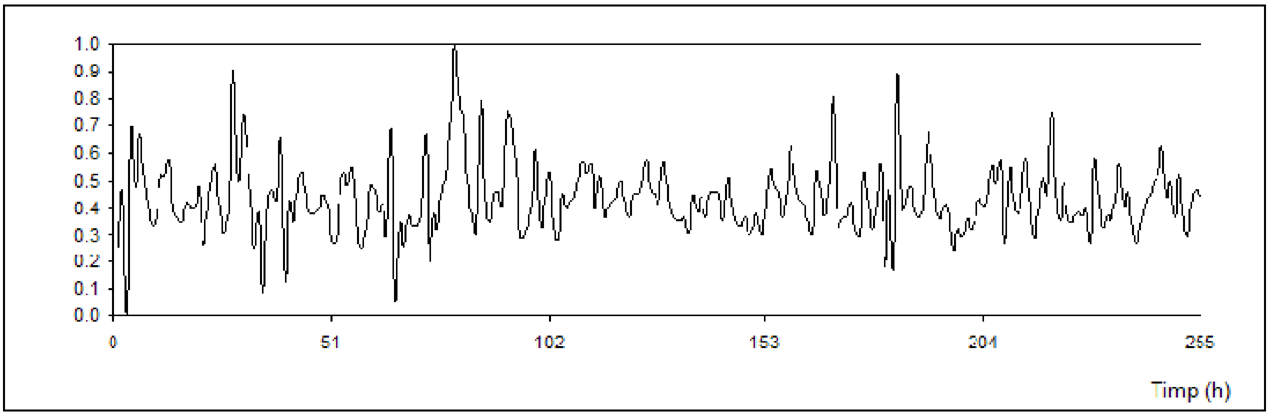
Fig. 9 - Computed and equivalent fuel flow (*series S2*) / *Debitul de combustibil calculat şi echivalent (seria S2).*



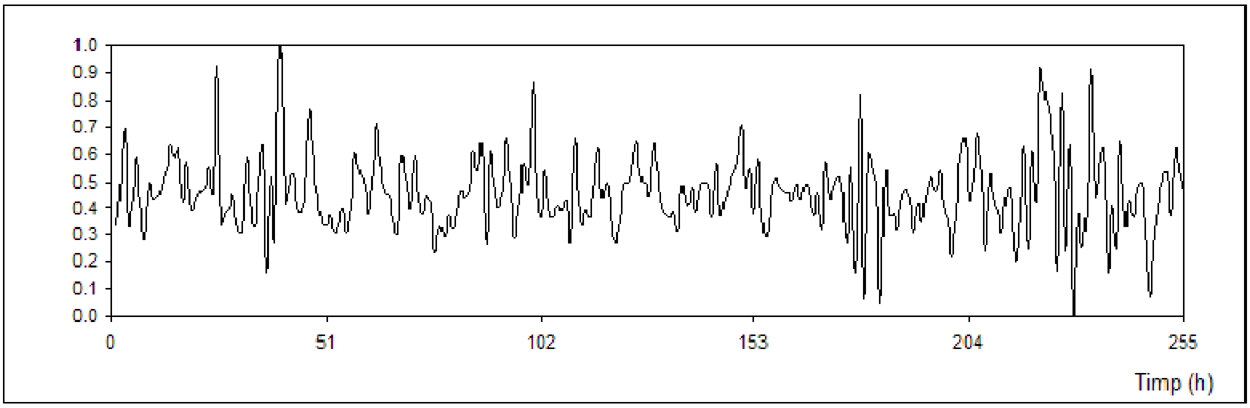
a) Gas temperature of the exit of the preheater, *S1 series / Temperatura gazelor evacuate din schimbătorul de căldură, seria S1.*



b) Gas temperature of the exit of preheater, *S2 series / Temperatura gazelor evacuate din schimbătorul de căldură, seria S2.*



c) Temperature of the excess air, *S1 series / Temperatura aerului în exces, seria S1.*



d)

Fig. 10 (a-d): d)Temperature of the excess air, *S2 series / Temperatura aerului în exces, seria S2.*

Table 2

Fractal dimension for all parameters, for both series, and for hourly and averaged evolutions
Dimensiunea fractală pentru toți parametrii, pentru ambele serii şi pentru evoluțiile orare şi mediate

Parameter / *Parametrul*	Fractal dimension / *Dimensiunea fractală*			
	S1		S2	
	Hourly *Valori orare*	Averaged *Valori mediate*	Hourly *Valori orare*	Averaged *Valori mediate*
Temperature of the excess air / *Temperatura aerului în exces,* ºC	1.42	1.04	1.43	1.02
Gas temperature at the exit of the preheater / *Temperatura gazelor evacuate din schimbătorul de căldură* , ºC	1.36	1.06	1.35	1.08
Clinker flow / *Debitul de combustibil*, t/h	1.19	1.05	1.18	1.03
Clinker temperature/ *Temperatura clincherului,* ºC	1.47	1.06	1.47	1.05
Equivalent fuel flow / *Debitul de combustibil echivalent*, t/h	1.33	-	1.32	-
Computed fuel flow / *Debitul de combustibil calculat*, t/h	1.29	1.05	1.29	1.04

- parameters' behavior can be *intuitively* viewed as being much closer for different series (*S1* and *S2*) of the same parameter rather than by comparing different parameters.

An insight of this issues has been done elsewhere [3, 4] but exceeds the objectives of this work, that are to provide accessible, easy to use methods/indicators.

A particular gauge that can be used to quantitatively characterize highly irregular curves is the ***F**ractal **D**imension* (*FD*). A mathematical exploration of this indicator is given in a review article [5]. Our intention is not to identify a fractal behavior of the time series but to provide a *quantitative* assessment that can be further analyzed and compared. Works on the fractal dimension (computed on fracture surfaces of several materials: cement, glass-ceramics and glass) can be found in [6-8], for example.

To obtain FDs for all parameters, we analyzed the time series. Scales were set for *x* and *y*-axis for all time series and only the plots themselves were analyzed. *Box-counting method* – see [9] for indepth information on its implementation - has been used for all determinations of the *FD*. We used two software packages: *Fractal Dimension Estimator* and, for confirmation, *ImageJ*. They both provided the same results. Results (Table 2) show that both hourly and averaged time series have very close or even identical values of the FD for each parameter when obtained on different series (*S1* and *S2*) thus confirming the intuitive observations.

Moreover, FDs are different from parameter to parameter, at least for the ones we used and especially for the irregular time series (hourly records). Correlations can be inferred for parameters that show close values of the FD, such as fuel flow and gas temperature, although they have to be further confirmed based on a sound analysis. For example, the amount of fuel burnt (fuel flow) and the gas temperature are directly related in real life clinkering plants' operation.

However, other parameters can affect the temperature at the exit of the preheater, for example the pressure drop and the amount of raw meal fed into the system. Though, the necessity for more in-depth investigations if it is the one's choice to isolate correlations.

4. Conclusions

This paper presents a series of heat balances made on the clinkering plant. For this purpose we used the same parameters, which were averaged over different time steps.

It was identified a stabilization of the most process parameters and specific heat consumption at around 100 hours of averaging.

Although the trends – at least – are well approximated for the computed and equivalent fuel flows, more observations (samples) and further analysis methods are needed to completely describe and predict the process evolution and parameters' association. The purpose of these analyzes would be to identify and eliminate incorrect data or/and with an exceptional character along with extracting further, helpful information about the process.

The process of averaging the parameters leads to smoother trends that can be easier to be examined and evaluated when monitoring the process. This could help to gain more insight of the factors that affect process efficiency and to correct them accordingly.

The *Fractal Dimension* proved to be a reliable indicator of the irregular behavior of the examined time series. It also proved to be specific for each process parameter. These observations conclude to the remark that *Fractal Dimension* can be used as a tool to diagnose and optimize the clinkering process.

REFERENCES

1. A.Radwan, Different Possible Ways for Saving Energy in the Cement Production, Advances in Applied Science Research, 2012, **3** (2),1162.
2. D.Radu, A. David and Z. Ghizdavet, The Influence of the Fuel Type on the Specific Heat Consumption of Clinkering Plants, Chemical. Bulletin. "POLITEHNICA" Univ. (Timişoara) 2010, **55** (69), 1.
3. Z.Ghizdavet, Romanian Journal of Materials, Knowledge discovery in industrial datasets: application part 1-analysis, 2010, **40**(2), 161.
4. Z.Ghizdăveţ, Romanian Journal of Materials, Knowledge discovery in industrial datasets: application part 2-prediction; 2011, **41**(1), 73.
5. M.Li, Fractal Time Series—A Tutorial Review, Mathematical Problems in Engineering (2010), Article ID 157264.
6. Y.Wang, S. Diamond, A fractal study of the fracture surfaces of cement pastes and mortars using a stereoscopic SEM method, Cement and Concrete Research 2001, **31**, 1385
7. T.Hill et al, Fractal analysis of toughening behavior in $3BaO{\cdot}5SiO_2$ glass-ceramics, Journal of American Ceramic Society, 2000, **83** (3), 545.
8. G.Baran et al, Fractal characteristics of fracture surfaces, Journal of American Ceramic Society, 1992, **75,** 2687.
9. J.Theiler, Estimating fractal dimension, J. Opt. Soc. Am. A, 1990, **7** (6), 1065

****

MANIFESTĂRI ŞTIINŢIFICE / SCIENTIFIC EVENTS

7–10 October
Recent Advances in Glass, Stained Glass, and Ceramics Conservation. ICOM-CC Working Group Glass and Ceramics Interim Meeting and Forum of the International Scientific Committee for the Conservation of Stained Glass (Corpus Vitrearum-ICOMOS), Amsterdam, The Netherlands.
Kate van Lookeren Campagne, Organising committee co-ordinator, Senior lecturer in Ceramic and Glass Conservation, University of Amsterdam, Hobbemastraat 22, 1071 ZC Amsterdam, The Netherlands.
Email icomcorpus2013@gmail.com
Web www.icomcorpus2013.nu

14–17 October
74th Conference on Glass Problems, Columbus, Ohio, USA.
Donna Banks, GMIC, 600 N. Cleveland Avenue, Suite 210, Westerville, Ohio 43082, USA.
Email dbanks@gmic.org
Web www.glassproblemsconference.org

23–26 October
Vitrum 2013, Milan, Italy.
Fiera Milano International, Piazzale Carlo Magno 1 - 20149 Milano, Milano, Italy.
Email gimav@gimav.it
Web www.vitrum-milano.it

27–31 October
MS&T'13: Materials Science & Technology Conference and Exhibition, combined with ACerS 115th Annual Meeting, Montréal, Québec, Canada
American Ceramic Society, Megan Mahan, 735 Ceramic Place, Suite 100, Westerville, Ohio 43081, USA.
Email mmahan@ceramics.org Web www.matscitech.org

25–27 November
Glasstech Asia, Kuala Lumpur, Malasia.
Aubrey Tham, CEMS, 1 Maritime Square #09-43 Harbourfront Centre Singapore 099253.
Email aubrey@cems.com.sg
Web www.glasstechasia.com.sg

****