Simplified Modeling of Clinker Cooling Based on Long Term Industrial Data

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Abstract: - The purpose of the present study is to develop a simplified dynamical model of clinker cooling process performed in grate coolers. The responses of three different pressures to changes of the speed of the first moving grate are modeled and the dynamical results are compared. The developed algorithm computes not only the average parameters but their uncertainty as well. The distributions of the dynamical parameters deviate significantly from the normal one in the most cases. The described simplified dynamics can be utilized for the effective parameterization of a robust controller regulating the clinker cooling process as well as for the construction of efficient simulators.

Key-Words: - Dynamics, Clinker, Cooler, Kiln, Model, Uncertainty

1 Introduction

Rotary kilns for clinker production are widely equipped with grate coolers. Heat transfer in coolers has an indirect impact on the performance of the entire burning line. A simplified flow sheet showing the basic components of a rotary kiln (RK) system is demonstrated in Figure 1.

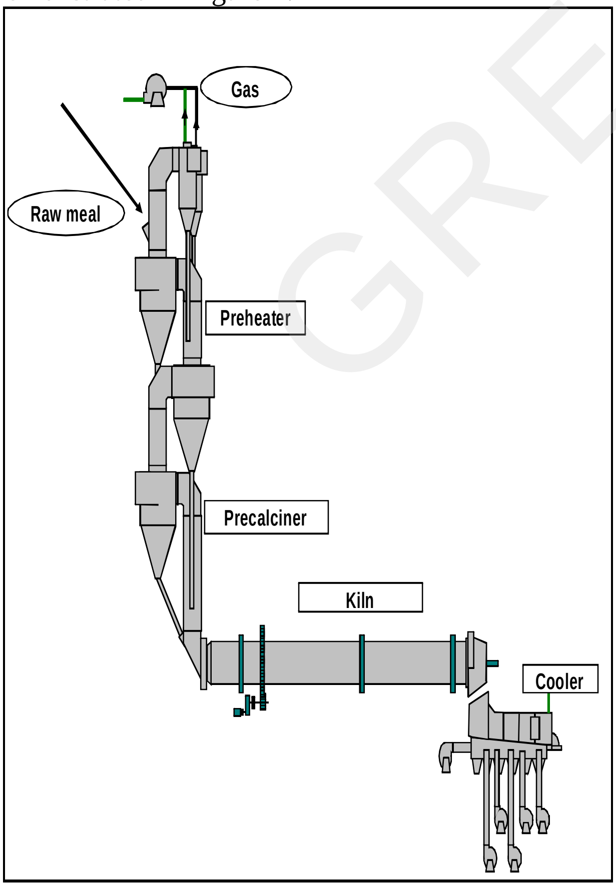

Figure 1.Clinker rotary kiln.

Raw meal is initially fed to the suspension preheater where it is heated and partially calcined from the hot gases coming from the kiln and precalciner. The decomposed material is introduced to the kiln where the calcination is completed and clinkerization follows. Afterwards clinker falls onto the grates of the cooler through the hood of kiln, and then it is unloaded into storage. The air volumes needed for the combustion come from the primary and secondary air. A schematic of a grate clinker cooler is shown in Figure 2.

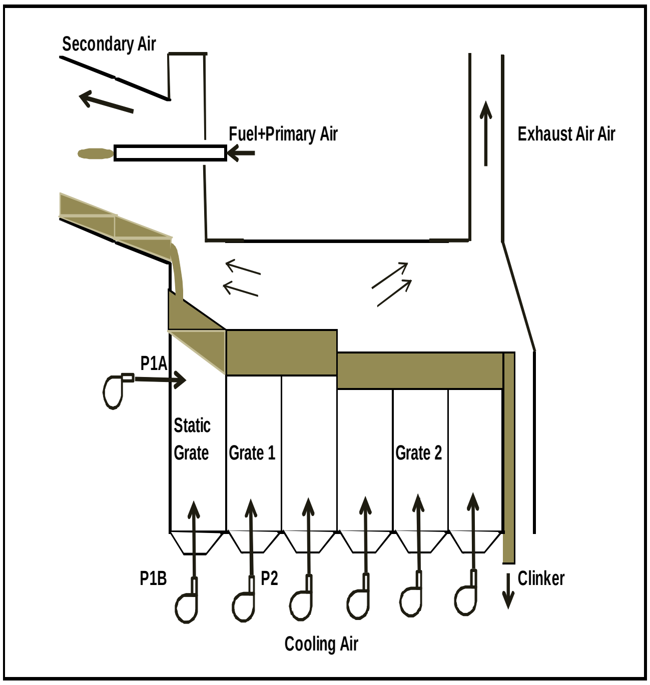

Figure 2.Grate cooler.

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Clinker cooling is achieved by passing air streams through the grates. Due to an oscillatory movement, the grates cause the flow and the spreading of the solid material. The thickness of the bed depends on the speed of the grates as well as on the mass rate of clinker in the kiln outlet. Consequently a heat exchange is performed between clinker and air. A part of the hot air volume is introduced inside kiln as secondary air and used for the fuel combustion, while the rest is evacuated towards the de-dusting filter characterized as exhaust air. Efficiency of the cooler includes two operations: (i) The heat recuperation from the clinker entering to the cooler, (ii) the cooling of the clinker. A fast cooling, i.e. a low clinker temperature in the installation outlet, contributes to an increase of the product quality [1]. Consequently the installation efficiency can be defined as follows:

$$\eta_{eff} = \frac{H_{sec}}{H_{Cl} + H_{air}} \qquad (1)$$

Where H_{Sec} = the heat of the secondary air, H_{Cl} = the heat of clinker in the kiln outlet, H_{air} = the heat of fresh air introduced to the cooler by the fans.

According to Harder [2] efficiency depends on the height of the clinker layer above the grates and passes from a maximum value. Therefore an adequate bed height is required. For process control purposes, the pressure under the grate of the cooler is monitored and considered as proportional to the thickness of the clinker bed. On the other hand to fulfill the basic role the cooler has, to transfer the clinker away from the kiln, sometimes an increase of the grate's speed is needed, to guaranty the operation reliability. In this case the retention time of the clinker drops, the thickness is decreasing and efficiency also is reduced. This conflict between efficiency and reliability is attempted to be solved by closing the loop between the speed of the grate and pressure. This task is satisfied by applying controllers of PID type or fuzzy logic techniques as well [3]. In spite of all the advances of the control during the last decades, PID controller remains the most common one. Effective design of this kind of controller needs the development of a dynamical model describing the process in the operating region.

The aim of the present study is to develop a reliable model of the dynamics between the speed of the first grate and clinker holdup within the cooler. An industrial pendulum cooler shown in Figure 2 with a static grate and two moving ones is modeled. The model coefficients and their uncertainty are calculated exclusively from routine process data without the need of any experimentation as usually the model identification needs. The simplified process model presented can be utilized to design or to tune controllers of different degree of complexity.

2 Process Model

In all the cases the dynamics between pressure and speed of the first grate is modeled. The speed of the second grate follows the first one, multiplied with a coefficient equal to 1.2. Between process and control variables a simplified model is adopted, involving time delay and integration. The same model is applied to a process of similar logic from Tsamatsoulis [4] and described by equations (1) to (3) in Laplace domain:

Transfer function between grate and speed:

$$G_p = \frac{x}{u} = \frac{k_v \cdot e^{-T_d \cdot s}}{s} \qquad (1)$$

$$x = a_x(P_0 - P) \qquad (2)$$

$$u = R_G - R_{G0} \qquad (3)$$

Where P = the pressure (mbars), x = the process variable, R_G=the speed of the grate, R_{G0} = the speed corresponding to P= P_0 of the steady state, u=the control variable, k_v = the gain and T_d = the delay time (min). The meaning of the coefficient α_x is the following: There are cases where the process output is not the process value but the ratio between P and the maximum one, P_{Max}, expressed as percentage. In this case α_x=100/ P_{Max}. Otherwise, if the process output is equal to P, then α_x=1. Additionally, to avoid undesirable noise, a first order filter is added to the pressure signal with time constant T_f equal to 0.25 min:

$$G_f = \frac{y}{x} = \frac{1}{1 + T_f \cdot s} \qquad (4)$$

The set of the model parameters consists of the gain k_v, delay time T_d, speed R_{G0} and pressure P_0, corresponding to system steady state. The model parameters are estimated using the convolution theorem between the input signal u and the process variable y, expressed by the equation (5).

$$y = \int_0^t u(\tau) g(t - \tau) d\tau \qquad (5)$$

Where g(t) is the pulse system response. Exclusively routine operation data of the cooler are utilized. These data are sampled on-line by applying

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convenient software. Time intervals equal to 250 minutes of cooler operation are selected as individual sets of data. The first 50 pairs of data are used to compute the initial convolution integral. Using a non linear method, the optimum four dynamical parameters are computed by minimizing the residual error provided by formula (6):

$$s_{res}^2 = \sum_{I=1}^{N} \frac{\left(P_{calc} - P_{exp}\right)^2}{N-k} \qquad (6)$$

Where s_{res} = the residual error, P_{calc} = the calculated pressure from the model application, P_{exp} = the actual one, N = the number of experimental points and k=the number of the independent model parameters. Using the residual error, the model regression coefficient is also determined for each experimental set.

3 Data Processing and Results

3.1 Results of Dynamical Parameters

Code in Visual Basic for Application was developed to process the large number of data. Because the model will be used for control purposes, a reliable dynamics shall be determined, with the minimum possible delay time. For this reason, the speed of first moving grate is correlated with the behavior of three pressures: (a) Pressures P1A, P1B of the fans providing air in the static grate and (b) pressure P2 corresponding to the fan supplying air to the moving grate. P2 is expressed as percentage of a maximum pressure of 80 mbars, while P1A, P1B are expressed as actual pressures. Afterwards the following steps are implemented:

(i) Around three months industrial data are used, with a sampling period of one minute. The total number of the experimental sets is 360.

(ii) For each data set the dynamical parameters are computed and the corresponding regression coefficient, R.

(iii) These results are filtered, permitting to pass only data sets presenting R ≥ 0.6. In this way the model's reliability augments.

(iv) The average values and the standard deviations are computed for the four model parameters.

(v) The coefficient of variation, %CV, for each parameter is found. Thus, a good approximation of the model uncertainty is achieved.

(vi) The model parameters and their uncertainty are presented in Table 1.

Table 1. Model parameters

	$k_v \times 10^2$			T_d (min)		
	Aver.	s	%CV	Aver.	s	%CV
P1A	5.12	3.05	59.6	5.0	3.8	74.1
P1B	4.90	3.33	67.9	5.4	4.6	84.3
P2	6.44	3.81	59.2	9.2	4.1	44.3
	R_0		P_0			
	Aver.	%CV	Aver.	%CV	s_{res}	R
P1A	18.2	27.0	61.0	37.6	2.2	0.74
P1B	18.1	27.3	69.1	31.1	2.2	0.74
P2	18.3	18.0	56.2	45.8	3.1	0.71

From these results the subsequent observations can be done:

- The dynamics between speed and pressures P1A, P1B is faster than the one with pressure P2 due to the lower delay time.
- The disadvantage of these two mentioned dynamics is the significantly larger uncertainty of T_d, compared with the delay of the third dynamics.
- The cause of this higher uncertainty is the frequent presence of coatings arriving from the kiln that decrease the retention time of the moving material in the static grate, while the pressure is kept high.
- The steady state pressures P_0 in first two dynamics are higher than the third because of the higher average pressure in this area. The difference in P_0 between P1A, P1B is probably due to the different air flow rate of the fans 1A, 1B.
- The steady state speed R_0 is equal for all the dynamical models, as it is defined from the average speed of the first moving grate.

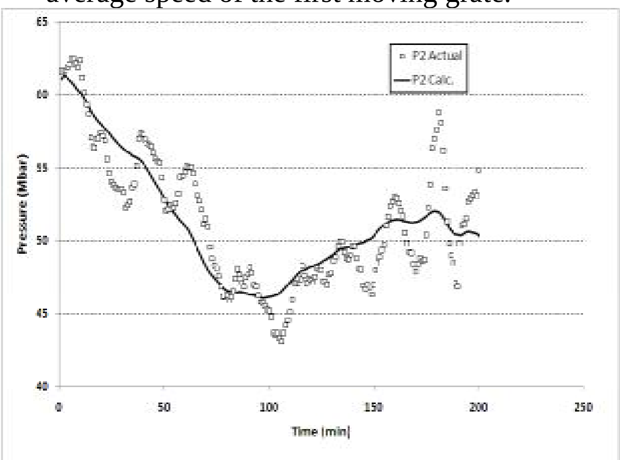

Figure 3. Model results

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- Parameters uncertainty is higher in the case of P1A, P1B. Consequently, despite the faster response of the pressures P1A, P1B to the changes of speed, the load disturbances are more intense compared with the pressure P2.
- All the above remarks have to be considered in the step of selection of the optimum loop between speed and pressure.

An example of the model application is shown in Figure 3. Despite the simplicity of the model, the experimental data are fitted well enough.

3.2 Distributions of Dynamical Parameters

Based on the large number of long term industrial data, the actual distributions of gain and delay time can be evaluated. These distributions are shown in Figures 4 to 9.

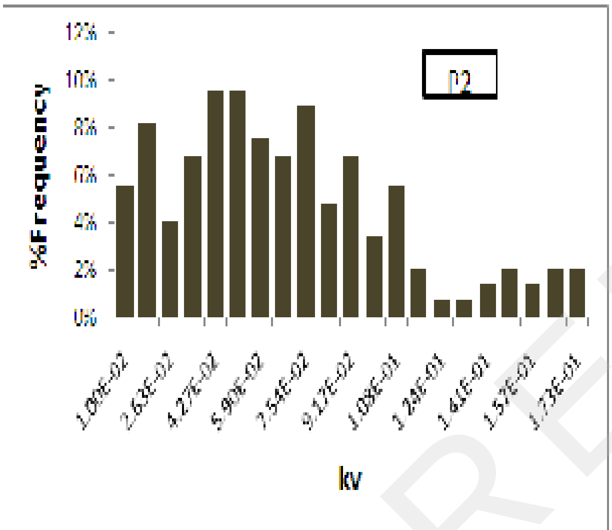

Figure 4. Gain distribution between P2 and speed.

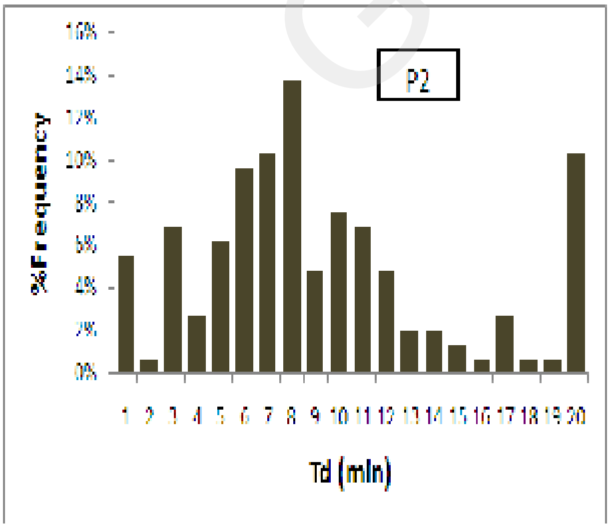

Figure 5. Time delay between P2 and speed.

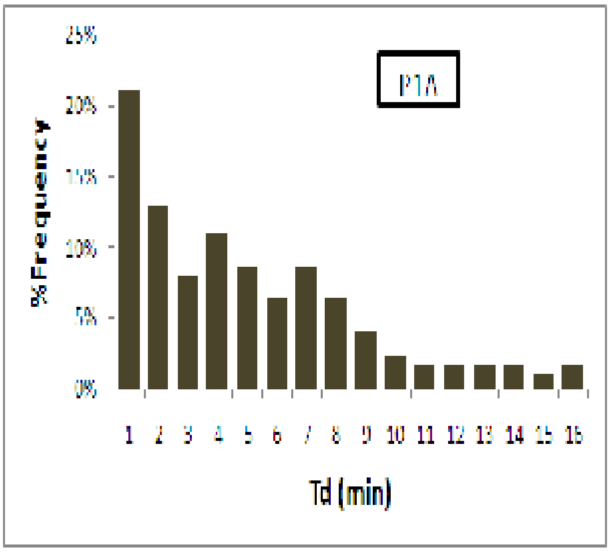

Figure 6. Gain distribution between P1A and speed.

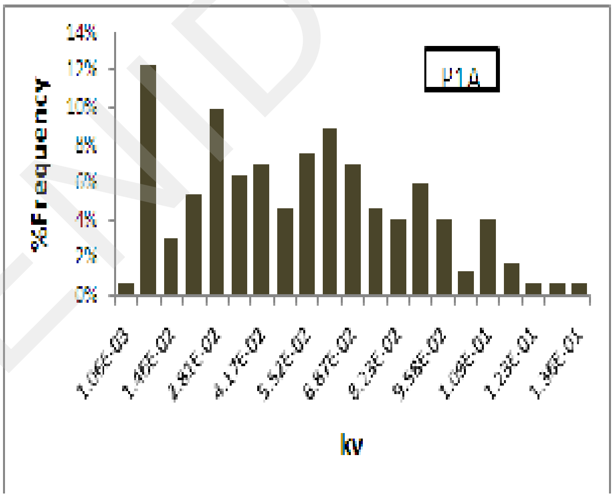

Figure 7. Time delay between P1A and speed.

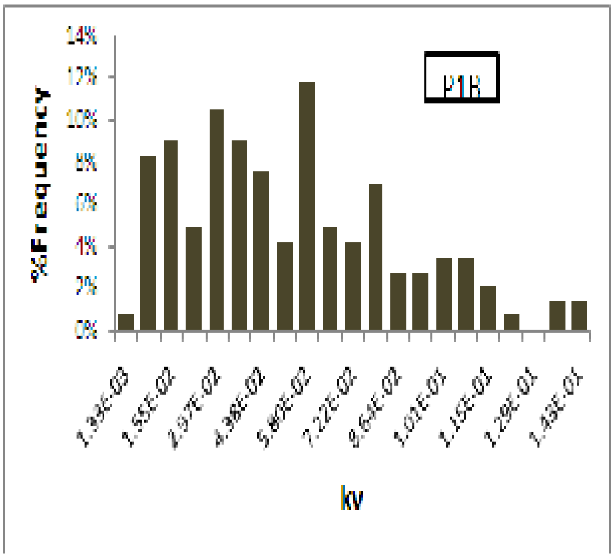

Figure 8. Gain distribution between P1B and speed.

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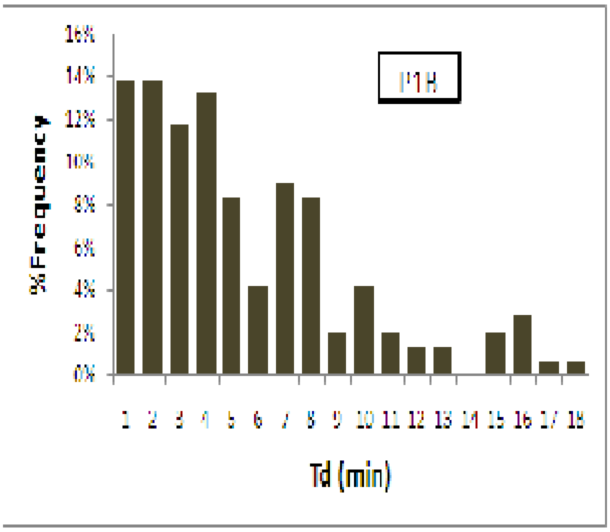

Figure 9. Time delay between P1B and speed.

From Figures 4 to 9 it can be seen that in the most cases the gain and delay distributions deviate considerably from the normal one. Consequently the big parameters uncertainty presented in Table 1 becomes more obvious from the plots of Figures 4 to 9. This conclusion has to be taken into account during the step of the controller design by introducing effective robustness criteria. Any efficient also simulation of the described cooling systems must incorporate the mentioned uncertainty.

4 Conclusions

In the present study the dynamic behavior of pendulum grate cooler is investigated by utilizing industrial scale data received online. In this way the laborious experimentation, creating problems to the kiln operation and to the product quality is avoided. The technique applied can be characterized as an identification "plant friendly" [5].

The dynamics between speed of the first grate and three pressures are determined using a simplified model containing integration and delay time: (a) Pressures P1A, P1B of the fans providing air in the static grate and (b) pressure P2 corresponding to the fan supplying air to the first moving grate. These dynamical models can be used to effectively design a controller regulating the cooling process. Each time four parameters are computed in order to fit the experimental data to the calculated ones. The uncertainty of each parameter is determined as well. The pressures P1A, P1B have a faster response to speed changes compared with the corresponding response of pressure P2. The disadvantage of these two dynamics compared with the third one is the higher uncertainty of the delay time, caused by the stronger load disturbances in the static grate.

Dynamical parameters in the most of the cases are not normally distributed. This important factor shall be taken into account in the step of the controller design, stabilizing the cooler operation.

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