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Experimental research on mathematical modelling and unconventional control of clinker kiln in cement plants

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Abstract. Analytical modeling of the flow of manufacturing process of the cement is difficult because of their complexity and has not resulted in sufficiently precise mathematical models. In this paper, based on a statistical model of the process and using the knowledge of human experts, was designed a fuzzy system for automatic control of clinkering process.

1. Introduction
The analytical identification of the process during the fabrication of the cement is difficult because this process is highly complex and they have helped us obtain some accurate mathematical methods who allow an effective conventional management.

According to the current evolution of the calculation techniques and of the process’ management principles, the experimental identification based on statistic data is an alternative we should consider.

The most usual methods are the system, the linear, and the discrete models who enclose the effect of the random disturbance, such as in Figure 1 [1].

![Figure 1. Discrete models [1]](image)

Synthetically speaking, z(t) is uptaken to this process (the parameter is the discreet time t). Because y(t) contains some noise (in addition), it is considered as such (it encloses a determination element x(t)). The statistic features of the output we have measured - y(t) - are determined by the statistic features of the noise z(t), or v(t), according to Figure 1. Due to the fact that the identification experiment does not use – for economic and engineering reasons – all the accomplishment of the noise, and/or either of the y(t) output, it does not acknowledge the identification methods of the output, because they need some statistic properties (hypothesis) which help them identify the PFD
pattern. This is not possible after only one significant experiment (for off-line identification methods) or after continuous process, but they have the same properties (for on-line identification methods).

In [2] was presented experimental statistical model drafted for a clinkering kiln. This model will be used in this paper to analyze the work regimes.

It considered the following variables:
- for input: - fuel flow - with significant effect in heat transfer and, indirectly, on features of chemical reactions in the kiln;
  - material flow;
- for output: - temperature of the combustion gas in the first heater;
  - actuating motor power of the kiln - is correlated with combustion zone temperature and quality of the clinker.

Although there are other possible variables, the variables mentioned are the most important and the identification process has been reduced to them.

Sizes measured in the process are represented in Figure 2.

![Figure 2: Representation of process inputs and outputs](image)

The proper shaping-up has been performed according to the CMP criterion – using two retrogressive methods – linear and non-linear II-type [2-4].

a) **Linear retrogressive**

If we use a linear subordination of the output size, according to the input sizes, we have:

\[
Y_1 = A_{11}X_1 + A_{12}X_2 + B_1, \quad (1)
\]

\[
Y_2 = A_{21}X_1 + A_{22}X_2 + B_2. \quad (2)
\]

By using the method of the smallest squares, the constant values are:
- for output size \( Y_1(t) \): \( A_{11} = 11.04; \quad A_{12} = -0.1055; \quad B_1 = 222.2 \)
- for input size \( Y_2(t) \): \( A_{21} = -85.92; \quad A_{22} = -3.784; \quad B_2 = 2265 \)

The precision indicator of the regress pattern is: \( R^2 = 0.9866 \)

The precision indicator of the regress pattern is: \( R^2 = 0.8266 \)
Thus, the pattern is:

\[
\begin{bmatrix}
Y_1 \\
Y_2
\end{bmatrix} = \begin{bmatrix} 11.04 & -0.1055 \\
-85.92 & -3.784
\end{bmatrix} \begin{bmatrix} X_1 \\
X_2
\end{bmatrix} + \begin{bmatrix} 222.2 \\
2265
\end{bmatrix}
\]  

(3)

b) II- degree polynomial regress

If we use a II-type non-linear subordination of the output size, according to the input sizes, we have:

\[
Y_1 = C_{11}X_1 + C_{12}X_2 + C_{13}X_1X_2 + C_{14}X_1^2 + C_{15}X_2 + C_{16}
\]

(4)

\[
Y_2 = C_{21}X_1 + C_{22}X_2 + C_{23}X_1X_2 + C_{24}X_2^2 + C_{25}X_1X_2 + C_{26}
\]

(5)

By using the method of the smallest squares the constant values are:

- for output size \( Y_1(t) \):
  \( C_{11} = -27.36; C_{12} = 1.628; C_{13} = 2.8; C_{14} = 0.001288; C_{15} = -0.1642; C_{16} = 273.6 \)

The precision indicator of the regress is: \( R^2 = 0.9988 \)

- for output size \( Y_2(t) \):
  \( C_{21} = -298; C_{22} = 170.9; C_{23} = 62.97; C_{24} = -0.1891; C_{25} = -6.506; C_{26} = -16317 \)

The precision indicator of the regress is: \( R^2 = 0.8576 \)

Thus, the pattern is:

\[
\begin{bmatrix}
Y_1 \\
Y_2
\end{bmatrix} = \begin{bmatrix} -27.36 & 1.628 & 2.78 & 0.001288 & -0.1642 \\
-298 & 170.9 & 62.97 & -0.1891 & -6.506
\end{bmatrix} \begin{bmatrix} X_1 \\
X_2 \\
X_1^2 \\
X_2^2 \\
X_1X_2
\end{bmatrix} + \begin{bmatrix} 273.6 \\
-16317
\end{bmatrix}
\]  

(6)

The number of processed data was not too high, resulting one degree of accuracy of about 0.9 for model determined, sufficient for its intended purpose.

Along with the experience of human experts, this model will allow the determination sets of rules for the synthesis of a fuzzy control system.

2. Control of clinker process

The objectives are: bringing and maintaining the operating parameters of the kiln to allow optimal values for increasing production and reduction of specific consumptions (energy and materials).

2.1. The structure of the control system [2], [5], [6]

The structure of the proposed system for automatically controlling the clinker process is shown in Figure 3.

The process is managed by a PLC (AP) equipped with modules I/O and network-connected to the higher level. Is proposed the use of smart sensors will communicate with the PLC via a local network. AP comprises a fuzzy controller whose the algorithm is described in the following paragraph. The other equipments used in the scheme are typified.

2.2. Control algorithm steps

a) Read the necessary parameters of process management: torque (CM); the temperature in the clinker zone (TZ); CO content output cyclones tower (COG); the kiln speed (TC); fuel flow (DJDC); feed rate flour branches A and B (AFA, AFB); blinds position VRA, VRB (DJVRA, DJVRB); oxygen to stage IV (OX). Required: coupling to the system of calculation of ten analog inputs.

b) Processing parameters sampled from the process as required calculation of input quantities.
c) Establish process condition at regular intervals (about 10 minutes) from the launch management strategy. System checks framing all input quantities in normal (N). If all input quantities are found in normal state, system becomes operational and launches first leading decision or adjust calculated output quantities and their new values. If one or more input quantities are not in normal situation, the system senses situation and launch an error message. The operator takes over control the process for to bring it in optimal condition.

d) During automatic control the system updates his status and validates a special situations (eg separation of shell).

e) Execution of orders in process is done at the times set by the system. For the implementation of controls, is necessary connect to the computing system of outputs for: flow supply flour arm A and arm B (CFAA CAFB), kiln speed (CTC), position blinds VRA and VRB (CDJVRA, CDJVRB), position valve for fuel flow adjustment (CDJDC).

3. **Fuzzy algorithm design**

For the synthesis of fuzzy algorithm was use a fuzzy controller developed starting from to on PIC 16C74 microcontroller and dedicated software for introducing rules, configuration settings, the shape of the membership functions, simulation. The program is functional only if Fuzzy controller is connected to the PC via the serial interface [2], [7], [8].

The program's main menu is presented with the default image activated (Figure 4). At the top of is entered the program name and the name loaded system. Bar following contains the main menu. Additionally, the left side of the bar is a visual function, with which subroutines at main program can be called.

3.1. **Information input data**

a) TZ - temperature in the clinkering area, °C

3-status: S – low 1100 ÷ 1300 °C; N – normal 1300 ÷ 1400 °C; R – high 1400 ÷ 1500 °C
b) PTZ - average slope on temperature in the area clinkering, degrees
   3-status: status -1 (-50 ÷ -15); status 0 (-15 ÷ 15); status 1 (15 ÷ 50)
   PTZ characterize temperature trend in the area combustion.

c) PC - average slope on torque, degrees
   5-status: status 0 (normal operation: -10÷10); status 1 (heating: 10÷20);
   status 2 (separation of shell: 20÷50); status -1 (cooling: -10÷-20);
   status -2 (strong cooling: -20÷-50)
   Torque defines the thermal load of the kiln. The delimitation status ranges is done by tracking into
running, because every kiln is defined from this point of view specifically.

d) AC - torque deviation from the reference value, %
   2-status: status – (-25 ÷ 0); status + (0 ÷ 25)
   AC defines the location of torque compared to the reference value, which the system it establishes
and it updates in running.

e) TC - kiln speed, rot/min
   2-status: status S (low: 1.3 ÷ 1.7); status N (normal: 1.7 ÷ 1.8)
   Speed is correlated with flour supply. In general, the supply increase/decrease at the same time
with increase/decrease speed.

f) NC - correlation level of speed with flour supplying, %
   2-status: status N (normal: 0 ÷ 90); status R (high: 90÷100)
   The correlation speed-supply with flour is specific to each kiln and is represented by a family of
speed-flow curves. R - means that it has reached the maximum level on supply (without increasing
speed).
By moving from one family with lower index at another with higher index can achieve a supply increase from stage to stage without changes in speed.

**g) DC - fuel flow - fuel oil, l/h**

2-status: status N (normal: 10000 ÷ 15000); status R (high: 15000 ÷ 16000)

The "DC" data was introduced to provide information on the possibility of increasing the flow of fuel, if conditions of the kiln permit. For example, where TZ is low (S) and a maximum "DC" (R), may not bring the kiln to a normal state by increasing the flow rate of the fuel supply, it will be necessary reduce the feed rate of the flour.

**h) COG - CO content in the flue gas to output of cyclones tower, %**

2-status: status N (normal: 0 ÷ 0.45); status R (high: 0.45 ÷ 0.6)

Maximum 0.6% CO is the value that triggers the electrostatic precipitator. CO value is a measure of the combustion quality and condition for electrostatic precipitator protection.

Membership functions for inputs are shown in Figure 5.

![Membership functions for inputs](image)

**Figure 5.** Membership functions for inputs

### 3.2. Information output data

**a) dCDC - fuel flow adjustment (by adjusting valve), l/h**

5 values: CM - increase much (400); CP - increase little (200); M – maintain (0); SP - decrease little (-200); SM - decrease much (-400)
b) dCNC - adjusting the level of correlation on flour supply and kiln speed
   3 values: C – increase (1); M – maintain (0); S – decrease (-1)

c) dCTC - adjustment the kiln speed, rot/min
   5 values: CM - increase much (0.2); CP - increase little (0.1); M – maintain (0);
   SP - decrease little (-0.1); SM - decrease much (-0.2)

d) dAFA, dAFB - flour feed rate, the branches A and B, t/h
   These flows are calculated based on the fuzzy value obtained for speed according 3.1.

e) TIMP - relaunch time of control, minutes
   3 values: A (12); B (16); C (18)

f) DJVRA, DJVRB - opening a blinds blowers: VRA and VRB, %. It is provided with a separate
   control loop, depending on the content of O2 in the fourth step.

   Membership functions for outputs are shown in Figure 6.

3.3. Control rules
Rule number = 5 * 2 * 3 * 3 * 2 * 2 * 2 * 2 = 1440 rules
An example of the control rules is given in Figure 7 and in Figure 8 shows the simulation of fuzzy
control for the dCDC size of command.

3.3. Control rules
Rule number = 5 * 2 * 3 * 3 * 2 * 2 * 2 * 2 = 1440 rules
An example of the control rules is given in Figure 7 and in Figure 8 shows the simulation of fuzzy
control for the dCDC size of command.
3.4. Static characteristics of designed fuzzy controller

Input data: TZ (temperature in the area clinkering), PTZ (average slope on temperature in the area clinkering), PC (average slope on torque), AC (torque deviation from the reference value), TC (klin speed), NC (correlation level of speed with flour supplying), DC (fuel flow), COG (CO content in the flue gas output cyclones tower).

The output: dCDC (fuel flow adjustment), dCNC (adjusting the level of correlation on flour supply and kiln speed), dCTC (adjustment the kiln speed), AFA, AFB (flour feed rate, the branches A and B), dJVRA, dJVRB (opening blinds Blowers VRA and VRB).

Was chosen for representation only the function $dCDC = f(TZ, PTZ)$ specified in the table inference given in Figure 6. Control surface obtained in this case is shown in Figure 9, considering variables TZ, PTZ (charts reasons, other inputs were considered constant).
In Figure 10 is illustrated plan static characteristic representation in coordinates (TZ, PTZ) through curves dCDC = const. This corresponds to dCDC inference table.

![Figure 10. Static characteristic](image)

The control system has been designed so that database, including the rules can always be improved, with the possibility of online testing. This flexibility allows continuous improvement of automat control, based on experience in the current running. After loading the rules base, the controller can work independently in the plant.

4. Conclusion

Usually, the lack of a firm mathematical model of the process is not an impediment for synthesis of a fuzzy automatic control. In relation to classical control, fuzzy control can be based and focused heavily on experience of human operator, experience which the Fuzzy controller can "shape" more accurately than a conventional controller.

To complex processes, it is recommended to have a mathematical model to can assess correlations between significant characteristic parameters of the process.

This is why was performed the approximate model of the clinking kiln. Since deterministic models may not take into account, in this case, all real phenomena from the kiln, it was done by a statistical identification. Using advanced methods of calculation, although the number of data processed was not too high, resulted a degree of accuracy of about 0.9 for kiln model, sufficient for its intended purpose.

A special problem is to establish the control rules and the decisions to be taken automatically, thanks to their direct technological implications and the multitude of practical situations that may arise. These issues directly influences the quality of expert system.

Consequently, there have been set very carefully control rules, based on the technological implications, the consultation of a large bibliography, discussions with specialists technologists.

In addition to the control algorithms it has been proposed a structure for the automation schema, using PLC which subsequently will be integrated into the overall system a production tracking. Were established thus sizes that must be measured in the process, the number of inputs / outputs, of the sampling interval and the necessary equipment. Through these specifications are emphasized practical aspects of theoretical research that enable their application in practice.
One of the great advantages of the proposed system is that the software has been designed so that the database, including the rules can always be improved, with the possibility of online testing. This flexibility allows continuous improvement of automat control, based on experience in the current running.

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