# IDENTIFICATION, CONTROL AND DECISIONS FOR HEATING PROCESSES

**Dumitru Popescu, Cătălin Dimon**

University Politehnica of Bucharest, Faculty of Automatics and Computer Science
Department of Automatics, Process Control and Computers
Splaiul Independentei 313, 060042, Bucharest, Romania

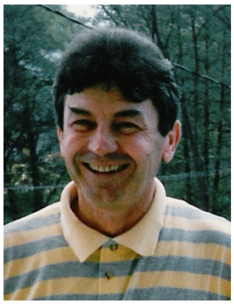
**dpopescu@indinf.pub.ro** *(Dumitru Popescu)*

**Abstract**

The paper presents some results of the research performed by the authors on control systems and optimization for the operating process of the heating installations from the blast furnace at a steel plant. This system was developed on two relevant levels: modeling and control level and optimization level, interconnected in a hierarchical control structure. The acquisition and control level was implemented using specialized microcontrollers. For this level, several systems have been analyzed, which can be grouped in two main categories: combustion control and heating control. The first category comprises fuel flow and combustion air flow, while the other category includes cold air flow and temperature. Since the fuel flow is obtained as a mixture of two out of three components: furnace gas, methane gas and coke gas, for each of them a flow control system is calculated. The supervisory level, concerning the optimization of the combustion process, was implemented on an operator console. Some constraints that determine the well-functioning of the system at desired parameters, such as cowper cupola temperature, residual gases temperature and CO concentration, are taken into account. The solution of the optimization problem represents the optimal decision, translated in real-time procedure as references for the acquisition and control level.

**Keywords: heat flows, identification algorithms, control system design, real-time systems, optimization problems.**

### Presenting Author's biography



Dumitru Popescu is a professor at the Automatic Control and Computer Science Faculty. He obtained the diploma of engineer in Electronics and Telecommunications at the University Politehnica of Bucharest (UPB) in 1966. He also obtained a diploma in Mathematics from the University of Bucharest in 1975. In 1978, he obtained his Ph. D. title in Automated Systems, at UPB. Since 1991, he is professor at the Automatic Control and Computer Science Faculty from UPB and director of the Research Centre in Automatics, Process Control and Computers (APCC). His teaching areas comprise Process Control and Advanced Automatics. Dumitru Popescu is also an associated teacher at universities from France and Italy and member of the IFAC Technical Committee for Bio-engineering and Chemical Processes.

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## 1 Introduction

The complexity of the metallurgical installations and the difficulties of planning and technological functioning are well known. Significant improvements for the heating steel plant installations area have been obtained when numerical equipments and modern theory of automatic control were introduced [1, 2].

In economic and commercial environments, quality and performance are very important criteria. The priorities in this type of processes are productivity, aw materials and the quality of products.

In this context, at ISPAT-SIDEX, an important steel plant in Eastern Europe, a program of modernization was launched in order to feed the plant's blast furnaces with hot air from the heating installations, referred further as cowpers.

The cowper's operating process has three work phases: heating, aeration and cooling. Using efficient synchronization and adequate technological switching, the cowpers are continuously feeding the blast furnace with hot air.

Some particularities of the process can be noticed. The large dimensions of the installation imply a plant model with large delays and distributed parameters, and engaging important flow materials.

The used fuel has many components: methane gas, coke gas and furnace gas, with different caloric powers. A convenient recipe must be calculated to feed the burners.

The quality of the combustion gas and the process nonlinearities introduce important disturbances in exploitation. To evaluate the combustion process, the composition of the residual gas is analyzed; more precisely, the concentrations of $O_2$ and CO are measured.

The major interest was to improve the cowper's efficiency using an adequate automation solution.

The work has been focused on two main directions:

- design of a data acquisition and control system to maintain the installation in a nominal operating point.

- optimization of the burning process, important consumer of fuel gas.

The conventional control solution, based on analogical systems [3], was replaced with numerical control. The numerical solution was computed using the model based - control design procedure, by poles-allocation methods for PID algorithms [4].

During the identification step RLS methods were introduced using the standard algorithms:

$$\begin{aligned} \hat{\theta}(k+1) &= \hat{\theta}(k) + F(k+1)\phi(k)\varepsilon^0(k+1), \ \forall k \in N \\ F(k+1) &= F(k) - \frac{F(k)\phi(k)\phi^T(k)F(k)}{1+\phi^T(k)F(k)\phi(k)} \\ \varepsilon^0(k+1) &= y(k+1) - \hat{\theta}^T(k)\phi(k), \ \forall k \in N \end{aligned} \tag{1}$$

with the following initial conditions:

$$F(0) = \frac{1}{\delta} I = (GI)I, \ 0 < \delta < 1 \tag{2}$$

The estimated $\hat{\theta}(k)$ represents the parameters of the polynomial plant model.

In the control design phase, the RST control algorithms were evaluated by poles allocation methods, covering the reference tracking and the disturbances rejection:

$$u(k) = \frac{T(z^{-1})}{S(z^{-1})} r(k) - \frac{R(z^{-1})}{S(z^{-1})} y(k) \tag{3}$$

Closed-loop poles are the roots of the polynomial $P(z^{-1}) = AS + BR$, which define the overall control performances.

The reference tracking is achieved through a reference model $\frac{B_m(z^{-1})}{A_m(z^{-1})}$, which generates the desired trajectory, based on the system reference [5].

Before the implementation stage, the performances of the designed systems have been verified by simulation. The authors had to make some improvements of the nominal control system using adaptive and robust control, to preserve the real-time performances [5]. Closed-loop system design was achieved with dedicated software, PIM-PCREG, which performs the identification and model based control design.

At the supervisory level, a mathematical global model has been obtained to describe the combustion process, using LS methods, based on the standard LS algorithm:

$$\hat{p} = (y^T y)^{-1} y^T z \tag{4}$$

where $\hat{p}$ is the vector of estimated parameters, $y$ is the input data acquisition matrix, and $z$ is the output data acquisition vector.

An optimization problem was built in restrictive conditions. The oxygen concentration in residual gas was chosen as quality criterion, depending on fuel gas flow $y_1$ and combustion air flow $y_2$:

$$\hat{z}(\%O_2) = f(y_1, y_2) \tag{5}$$

 

with the following technological constraints:

$$\begin{aligned} & y_{1L} \le y_1 \le y_{1H} \\ & y_{2L} \le y_2 \le y_{2H} \\ & \hat{z}_{1L} \le \hat{z}_1(y_1, y_2) \le \hat{z}_{1H} \\ & \hat{z}_{2L} \le \hat{z}_2(y_1, y_2) \le \hat{z}_{2H} \\ & \hat{z}_{3L} \le \hat{z}_3(y_1, y_2) \le \hat{z}_{3H} \end{aligned} \quad (6)$$

The implicit constraints, evaluated by the same LS identification procedure, are imposed for the functions $\hat{z}_1$ (CO concentration), $\hat{z}_2$ (cowper cupola temperature), $\hat{z}_3$ (flue gases temperature), evaluated as the criterion-function $\hat{z}(\%O_2)$.

The solution $(y_1^*, y_2^*)$ of the optimization problem (4), (5) was obtained using Boxe method and SISCON software package [6].

This software is written in C++ language, solves the global optimization problem and determines also the mathematical decision models of the systems, which may be either linear or non-linear. The syntactic analyzer, which reads and interprets the functions, handles almost any type of non-linearity. It gives also the possibility to select the input variables or to automatically generate combinations of input variables in order to find the closest combination to reality. The data can be taken from text files or can be directly entered by using the keyboard. The user can select the optimization method, depending of the specific optimization problem.

## 2 Data Acquisition and Control Level Design

The chosen automation solution assures the heating control, and the recipe of fuel gas composition. Twenty-one parameters are measured, and seven of them are controlled [4, 7, 8].

### 2.1 Combustion process control

The combustion control provides two separated control systems, one for the fuel flow (FRC-1) and another for combustion air flow (FRC-2) in order to maintain an operating combustion point. The quality of the combustion process is evaluated measuring the quality of residual gases (%$O_2$, %CO).

Considering the importance of FRC-1 and FRC-2, in Fig. 1 and Fig. 2 are presented time-response graphics for these two systems.

For FRC-1 the following model has been identified:

$$\begin{aligned} \hat{B}_1 &= 0.19\, z^{-1} \\ \hat{A}_1 &= 1 - 0.905\, z^{-1} \end{aligned} \quad (7)$$

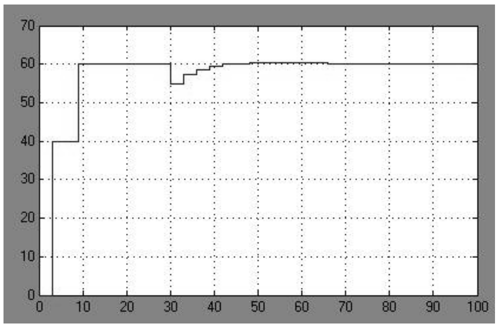


Fig. 1 Reference tracking and disturbance rejection for FRC-1

For FRC-1, the desired performances are given as follows:
- disturbance rejection:

$$P(z^{-1}) = 1 - 1.314\, z^{-1} + 0.432\, z^{-2} \quad (8)$$

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.067 + 0.051 z^{-1}}{1 - 1.314\, z^{-1} + 0.432\, z^{-2}} \quad (9)$$

The correspondent numerical RST algorithm has been calculated:

$$\begin{aligned} R_1 &= 0.5907 - 0.4731\, z^{-1} \\ S_1 &= 0.1903 - 0.1903\, z^{-1} \\ T_1 &= 1 - 1.314094\, z^{-1} + 0.43171\, z^{-2} \end{aligned} \quad (10)$$

During the implementation phase, the control algorithm was used in an adaptive version. The model $(\hat{A}_1^k, \hat{B}_1^k)$ is changed to $(\hat{A}_1^{k+1}, \hat{B}_1^{k+1})$, and for $(P_1^{k+1} = P_1^k = P_1)$, $(R_1^k, S_1^k)$ is then changed to $(R_1^{k+1}, S_1^{k+1})$, to preserve the real-time performances. The closed-loop identification step has been achieved using the RLS algorithms, where the adaptive error $e_1{}^k$ was replaced with the adaptive filtered error $e_{1f}{}^k$:

$$e_{1f}{}^k = \frac{S_1^k}{P_1}(\hat{A}_1^k y_1^k - \hat{B}_1^k u_1^k) \quad (11)$$

For FRC-2 system a similar model has been identified:

$$\begin{aligned} \hat{B}_2 &= 0.19\, z^{-1} \\ \hat{A}_2 &= 1 - 0.904\, z^{-1} \end{aligned} \quad (12)$$

For FRC-2, the desired performances are given as follows:
- disturbance rejection:

$$P(z^{-1}) = 1 - 1.314\, z^{-1} + 0.432\, z^{-2} \quad (13)$$

 

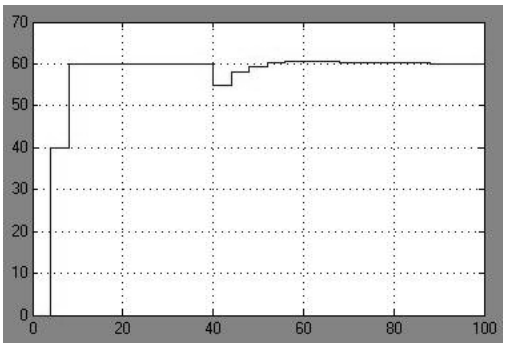


Fig. 2 Reference tracking and disturbance rejection for FRC-2

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.067 + 0.051 z^{-1}}{1 - 1.314 z^{-1} + 0.432 z^{-2}} \quad (14)$$

The correspondent RST algorithm was:

$$\begin{aligned} R_2 &= 0.455 - 0.372 z^{-1} \\ S_2 &= 0.19 - 0.19 z^{-1} \\ T_2 &= 1 - 1.460 z^{-1} + 0.533 z^{-2} \end{aligned} \quad (15)$$

The optimal values for the fuel flow and the combustion air flow are calculated at the supervisor level and transferred automatically in the configuration of the two control loops. Therefore is assured an optimal flow ratio for the combustion process.

### 2.2 Heating Process Control

Two control systems are provided, one to control the cold air flow (which must be heated) and the other to control the temperature of hot air entering the furnace.

For FRC-3 (cold air flow control system), the identified model is:

$$\begin{aligned} \hat{B}_3 &= 0.04 z^{-1} \\ \hat{A}_3 &= 1 - 0.91 z^{-1} \end{aligned} \quad (16)$$

For FRC-3, in terms of performances we have:
- disturbance rejection:

$$P(z^{-1}) = 1 - 1.31 z^{-1} + 0.43 z^{-2} \quad (17)$$

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.07 + 0.05 z^{-1}}{1 - 1.31 z^{-1} + 0.43 z^{-2}} \quad (18)$$

The correspondent RST algorithm was:

$$\begin{aligned} R_3 &= 0.27 - 0.23 z^{-1} \\ S_3 &= 0.04 - 0.04 z^{-1} \\ T_3 &= 1 - 1.63 z^{-1} + 0.67 z^{-2} \end{aligned} \quad (19)$$

For hot air temperature control system TRC-4, the following model was identified:

$$\begin{aligned} \hat{B}_4 &= 0.068 z^{-1} + 0.052 z^{-2} \\ \hat{A}_4 &= 1 - 1.33 z^{-1} + 4.49 z^{-2} \end{aligned} \quad (20)$$

The desired performances are given as follows:

- disturbance rejection:

$$P(z^{-1}) = 1 - 1.314 z^{-1} + 0.432 z^{-2} \quad (21)$$

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.067 + 0.051 z^{-1}}{1 - 1.314 z^{-1} + 0.432 z^{-2}} \quad (22)$$

and the correspondent algorithm was implemented

$$\begin{aligned} R_4 &= 8.357 - 11.111 z^{-1} + 3.754 z^{-2} \\ S_4 &= 1 - 0.566 z^{-1} - 0.433 z^{-2} \\ T_4 &= 8.357 - 11.111 z^{-1} + 3.754 z^{-2} \end{aligned} \quad (23)$$

The non-linear components of the system structure imposed a robust implementation of this algorithm. Robust design was based on sensitivity function and disturbance-output. To assure a specific shaping of the sensitivity function, pre-specified polynomials $H_{R4}$, $H_{S4}$ were introduced.

Consequently, the implemented algorithm became:

$$R_4^{'} = R_4 \cdot H_{R4} \quad (24)$$

$$S_4^{'} = S_4 \cdot H_{S4} \quad (25)$$

where $H_{R4}$ and $H_{S4}$ introduce zeros at predetermined frequencies for convenient adjustment of the sensitivity function (the $H_{R4}$ zeros at low frequencies and the $H_{S4}$ zeros at band-pass intermediate frequencies for the closed-loop system).

Finally, the fuel gas flow recipe is assured by systems controlling the ratio between furnace gas flow, methane gas flow and coke flow.

The control systems FRC-5, FRC-6 and FRC-7 respectively have been calculated during the design phase. For the most important control system, FRC-6, the time response is presented in Fig. 3.

The model obtained for FRC-5 was:

$$\begin{aligned} \hat{B}_5 &= 0.038 z^{-1} \\ \hat{A}_5 &= 1 - 0.908 z^{-1} \end{aligned} \quad (26)$$

For FRC-5, in terms of performances we have:

- disturbance rejection:

$$P(z^{-1}) = 1 - 1.314 z^{-1} + 0.432 z^{-2} \quad (27)$$

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- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.067 + 0.051 z^{-1}}{1 - 1.314 z^{-1} + 0.432 z^{-2}} \quad (28)$$

The correspondent RST algorithm was:

$$\begin{aligned} R_5 &= 0.27 - 0.234 z^{-1} \\ S_5 &= 0.038 - 0.038 z^{-1} \\ T_5 &= 1 - 1.635 z^{-1} + 0.671 z^{-2} \end{aligned} \quad (29)$$

The model and output control for FRC-6:

$$\begin{aligned} \hat{B}_6 &= 0.031 z^{-1} \\ \hat{A}_6 &= 1 - 0.905 z^{-1} \end{aligned} \quad (30)$$

For FRC-6, in terms of performances we have:
- disturbance rejection:

$$P(z^{-1}) = 1 - 1.314 z^{-1} + 0.432 z^{-2} \quad (31)$$

- reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.067 + 0.051 z^{-1}}{1 - 1.314 z^{-1} + 0.432 z^{-2}} \quad (32)$$

The RST algorithm obtained was:

$$\begin{aligned} R_6 &= 0.27 - 0.234 z^{-1} \\ S_6 &= 0.031 - 0.031 z^{-1} \\ T_6 &= 1 - 1.635 z^{-1} + 0.671 z^{-2} \end{aligned} \quad (33)$$

Finally, for FRC-7 the identified model had the following form:

$$\begin{aligned} \hat{B}_7 &= 0.476 z^{-1} \\ \hat{A}_7 &= 1 - 0.905 z^{-1} \end{aligned} \quad (34)$$

For FRC-7, the specified performances were:
- for disturbance rejection:

$$P(z^{-1}) = 1 - 1.314 z^{-1} + 0.432 z^{-2} \quad (35)$$

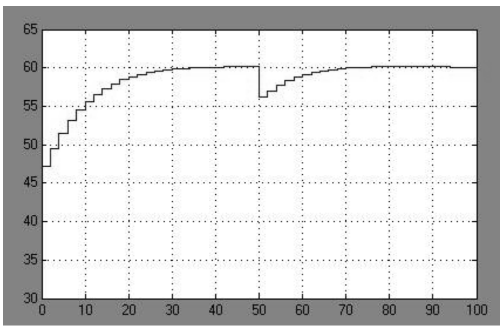


Fig. 3 Reference tracking and disturbance rejection for FRC-6

- for reference tracking:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.067 + 0.051 z^{-1}}{1 - 1.314 z^{-1} + 0.432 z^{-2}} \quad (36)$$

The computed RST numerical algorithm was:

$$\begin{aligned} R_7 &= 0.096 - 0.857 z^{-1} \\ S_7 &= 0.476 - 0.476 z^{-1} \\ T_7 &= 1 - 1.809 z^{-1} + 0.819 z^{-2} \end{aligned} \quad (37)$$

The hardware implementation for the data acquisition and control level was accomplished on a two 16-bits micro-controllers configuration connected to the process.

## 3 Optimization level design

The purpose of the decision level is to optimize the combustion process in restrictive technological conditions [9, 10, 11].

First of all, a supervisory model (Fig. 4) has been evaluated: $z(\%O_2) = f(y_1, y_2)$. The constraints models: CO concentration ($\hat{z}_1$), cowper cupola temperature ($\hat{z}_2$) and residual gases temperature ($\hat{z}_3$), all of them depending on fuel flow ($y_1$) and combustion air flow ($y_2$), were also calculated:

$$\begin{aligned} \hat{z}_1(\%CO) &= f_2(y_1, y_2) \\ \hat{z}_2(T_{cowper\,cupola}) &= f_3(y_1, y_2) \\ \hat{z}_3(T_{flow\,gases}) &= f_4(y_1, y_2) \end{aligned} \quad (38)$$

These models have been computed using LS experimental identification method [12].

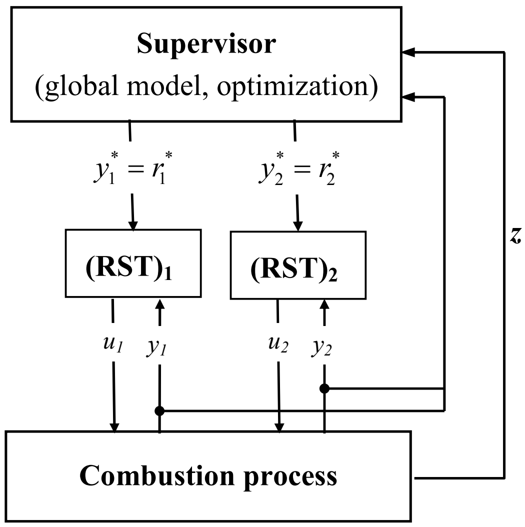


Fig. 4. Supervisory control level

The procedure of data acquisition is accomplished during the first interval of cowper heating phase, on an imposed duration, with an acquisition rate of 2 seconds and a resolution of 256 observations.

For the usual data set, measured in real-time conditions, the following non-linear models are estimated:

$$\begin{aligned} \hat{z} &= -9.665 + 0.229\,y_1 - 0.0009\,y_1^2 + 0.0104\,y_2 \\ \hat{z}_1 &= 4282.875 - 21.566\,y_1 - 0.077\,y_1^2 - 21.500\,y_2 \\ \hat{z}_2 &= 1277.613 + 0.001\,y_1^2 - 0.387\,y_2 \\ \hat{z}_3 &= 499.162 - 0.002\,y_1^2 - 3.499\,y_2 \end{aligned} \quad (39)$$

A parametric optimization problem was built, which, for the considered example, is stated as follows:

$$\min_{y_1, y_2} z = -9.665 + 0.229\,y_1 - 0.0009\,y_1^2 + 0.0104\,y_2 \quad (40)$$

with the following restrictions:

$$\begin{aligned} 0 &\le \hat{z}_1 \le 450\,ppm \\ 0 &\le \hat{z}_2 \le 1300^o C \\ 0 &\le \hat{z}_3 \le 340^o C \\ 96.309 &\le y_1 \le 102.452 \\ 46.602 &\le y_2 \le 57.992 \end{aligned} \quad (41)$$

The solution is the optimal operating point for the combustion process:
– air combustion flow: $y_1^* = 97.469\ m^3/h$,
– fuel flow: $y_2^* = 47.804\ m^3/h$,
for which it results a minimum value of $O_2$ concentration in flue gases:

$$z_{\min}(\%O_2) = 4.6\% \quad (42)$$

At the same time, corresponding values are obtained for the constraints measures:

$$\begin{aligned} z_1(\%CO) &= 415.73\,ppm \\ z_2(T_{cupola}) &= 1273.25\,^oC \\ z_3(T_{flue\,gases}) &= 311.47\,^oC \end{aligned} \quad (43)$$

The computed optimal point, meaning optimal decision $(y_1^*, y_2^*)$, is automatically transferred as reference $(r_1^* = y_1^*, r_2^* = y_2^*)$ to the inferior control level, which has the task to bring the combustion process at this optimal exploitation point.

The decision level is implemented on the operator console of the numerical equipment.

Analyzing the obtained values there can be noticed a decrease in the concentration of $O_2$ by 3.15% :

$$I_{O_2} = \left| \frac{4.6 - 4.75}{4.75} \right| \cong 3.15\% \quad (44)$$

which implies a medium reduction in fuel flow by 12.52% :

$$I_{fuel} = \left| \frac{47.804 - 54.649}{54.649} \right| \cong 12.52\% \quad (45)$$

where *54.649* is the mean value for fuel flow, obtained from the experimental data and *47.804* is the optimal value above-mentioned.

Estimating that 57.5% of the fuel flow is represented by methane gas, which implies a medium reduction in methane gas flow by 7.2%, a decrease of $350\,m^3/h$ will be achieved in the demand for methane gas. Taking into account its price, at about 135$ for $1000\,m^3/h$, it results a saving of $47\,\$/h$, which would lead to approximately $340000\ \$/year$ savings.

## 4 Conclusions

This paper presents a numerical control and optimization solution for air heating installations in a steel plant in Romania.

The system was implemented as a hierarchical structure, organized on two interconnected levels, data acquisition and control level, and supervisory level, respectively.

For the first level, the design methodology uses software resources, based on experimental identification techniques and on pole-allocation methods to compute the control algorithms.

To improve control systems performances, adaptive and robust mechanisms were used during the implementation phase.

The second hierarchical level evaluates the optimal decision for the combustion process, solving a parametric optimization problem.

The system is implemented as a real time industrial application, on the blast furnace no. 5 in ISPAT-SIDEX Galati.

The full results of our project, implemented at ISPAT-SIDEX Galati, have been presented in this paper.

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