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# DIGITAL CONTROL ECOSYSTEM FOR STEEL PLANT INSTALLATIONS

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**Rezumat.** *Articolul propune un sistem de control pentru o instalație de încălzire a aerului care alimentează un furnal. Obiectivul principal constă în proiectarea și implementarea unei soluții adecvate acestui tip de proces care asigură o prelucrare eficientă a instalației și optimizează procesul de combustie, o sursă de poluare recunoscută la nivel industrial. Structura de control este organizată ierarhic pe două niveluri: nivelul de execuție care controlează parametrii cheie ai procesului de combustie și încălzire a aerului și nivelul de supervizare care optimizează procesul de combustie necesar încălzirii aerului și minimizează gradul de poluare a mediului înconjurător.*

**Abstract.** *The paper proposes a system control configuration for air heating installations which aliment the blast furnaces. The main objective is to design and implement an adequate solution for this type of process which ensures efficient treatment for heating the air of the steel plant and optimizes the combustion process, an important supplier of the required energy and a recognized industrial source of pollution. The proposed control structure for the air heating process is organized across two interconnected levels in a hierarchical configuration: the execution level to control the key parameters of the combustion process and the heating air process and the supervision level for optimizing the combustion process, necessary for heating the air and for minimizing the degree of environment pollution, respectively.*

**Keywords:** Steel plant, control, optimization, pollution

## 1. Introduction

The complexity of metallurgic and steel facilities and their operational difficulties are well known. This type of installation is recognized as the sources of pollution in industrial environment [1, 2].

Significant improvements in the operation of these facilities were achieved after the emergence of digital control and high-performance computing equipment [8].

Economically and commercially, the most important evaluation criteria in a steel plant are price, quantity and quality of production.

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The current priorities in the iron and steel industry are energy saving, productivity and product diversification and the minimizing of the pollution level. [9].

There are some particularities for these installations (technologically known as cowpers):

- the rather large dimensions lead to mathematical models with significant delay or distributed parameters;
- the great values of flaw materials used in the technological process, and the several components mixed in a random manner for the combustion gas (methane gas, coke gas and blast furnace gas), which all have different heating capacities;
- non-linearity of the technological setup.

All these particularities present significant difficulties in the operation of heating air process.

The operating mechanism of these installations comprises three important steps: the actual heating of the air for the blast furnace, the supply of air and the cooling of the installation. By using an efficient technological switching through suitable means, the furnace is supplied with about 50.000 m³/h hot air, at 1200°C.

A technological representation of the installation can be observed in figure 1.

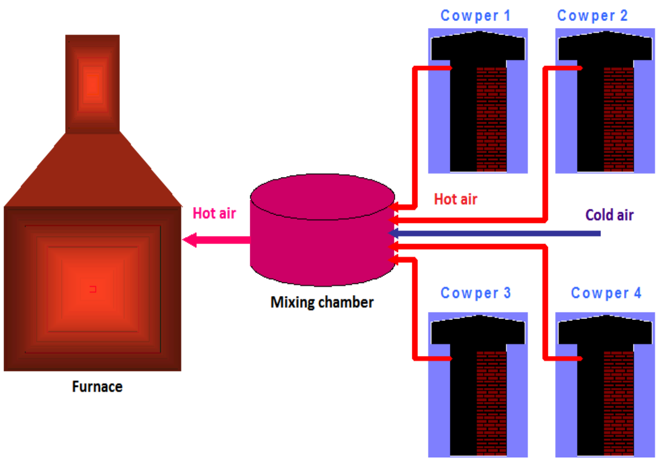


**Fig. 1.** Technological configuration of heating air installation.

## 2. Numerical control design

In terms of control level, using the dedicated software for model control-based design, the dynamic models of the key process parameters are obtained by experimental identification techniques (WINPIM) [10, 11] and the polynomial control algorithms are computed using the pole allocation method (WIREG) [12, 13].

The solution proposed for the execution (regulation) level is based on two aims.

a) control of the combustion process that is responsible for the amount of heat required for heating the installation in order to control the combustion flow and air flow that maintain the combustion;

b) control of the air heating process parameters that will supply the blast furnace by regulating the air flow introduced in the cowper and temperature of air at the entrance of the blast furnace.

Combustion control includes closed loop systems for the fuel flow rate (FRC-1), which complies with the set-point of 98.000 $m^3/h$ and for the combustion air flow (FRC-2), which respects the set-point with the value of 49.000 $m^3/h$. Both systems control the thermal energy required to heat the air in the system.

To control the heating of air in a blast furnace, closed-loop systems are used: (FRC-3) for the flow that supplies the air heating system at the inlet of the blast furnace at a set-point of 50.000 $m^3/h$ and (TRC4) for the air temperature that complies with the set-point of 1200 °C.

For the numerical control design, we propose a polynomial algorithm and the pole placement method with independent objectives. This approach consists in obtaining the desired behavior of the system during tracking (set-point change), independently from the behavior imposed during regulation (disturbance-rejection), using the same control algorithm [15, 16].

The structure of the closed loop system is represented in Figure 2.

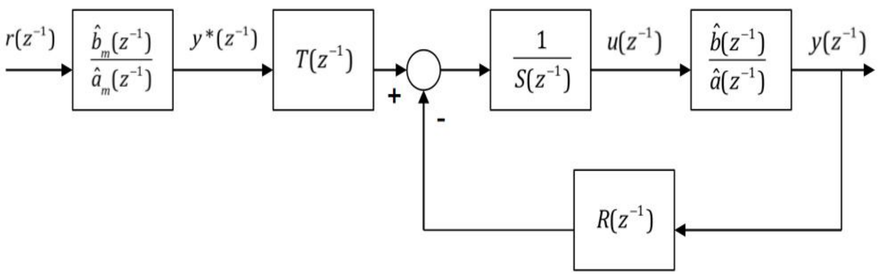


**Fig. 2.** Closed loop numerical system.

The temperature within the median section of the reactor is regulated by the control of the quantity of methane used in the combustion process that heats the plant. The automation solution should be able to provide the possibility of maintaining the temperature values within a range of 820 °C and 860 °C.

The control strategy enables a digital (RST) controller to be calculated without any restriction on the degrees of the polynomials $\hat{a}(z^{-1})$ and $\hat{b}(z^{-1})$ for the discrete model of the process.

The output of the tracking model $\hat{b}_m(z^{-1})/\hat{a}_m(z^{-1})$ specifies the desired trajectory $y^*(z^{-1})$ that the output of the closed loop system must track.

The polynomial $T(z^{-1})$ will ensure the imposed tracking condition $y(z^{-1}) = y^*(z^{-1})$.

The closed loop poles are defined by the desired characteristic polynomial $P_i(z^{-1})$. The computation of the polynomials $R(z^{-1})$, $S(z^{-1})$ and $T(z^{-1})$ takes place in two steps.

Using $R(z^{-1})$ and $S(z^{-1})$, the poles specified by $P_i(z^{-1})$ (regulation objective) are placed in closed loop. The second step, the polynomial $T(z^{-1})$ is determined in order to find the reference trajectory $y^*(z^{-1})$ and to assure the output of the global control system to reference trajectory.

By eliminating the tracking generator $\hat{b}_m(z^{-1})/\hat{a}_m(z^{-1})$ and the pre-compensator $T(z^{-1})$ of the diagram in Figure 2, the transfer function in closed loop with stable zeros is expressed as follows:

$$G_{RS}\left(z^{-1}\right) = \frac{\hat{b}\left(z^{-1}\right)}{\hat{a}\left(z^{-1}\right)S\left(z^{-1}\right) + \hat{b}\left(z^{-1}\right)R\left(z^{-1}\right)} \tag{1}$$

The following condition is imposed:

$$G_{RS}(z^{-1}) = \frac{1}{P_i(z^{-1})} \tag{2}$$

As the polynomial $P_i(z^{-1})$ is specified *a priori*, the following computation strategy is proposed.

We start by the polynomial equation:

$$\hat{a}\left(z^{-1}\right)S\left(z^{-1}\right) + \hat{b}\left(z^{-1}\right)R\left(z^{-1}\right) = \hat{b}\left(z^{-1}\right)P_i(z^{-1}) \tag{3}$$

which allows $R(z^{-1})$ and $S(z^{-1})$ to be calculated.

Equation (3) demonstrates the way the denominator of the transfer function $G_{RS}(z^{-1})$ must be factorized by $\hat{b}\left(z^{-1}\right)$. This operation leads to a natural factorization for $S(z^{-1})$:

$$S\left(z^{-1}\right) = \hat{b}\left(z^{-1}\right)S'\left(z^{-1}\right). \tag{4}$$

The expression from equation (3) is simplified and results:

$$\hat{a}\left(z^{-1}\right)S'\left(z^{-1}\right) + R\left(z^{-1}\right) \equiv P_i\left(z^{-1}\right) \tag{5}$$

This equation has a single unique solution for:

$$\begin{cases} rank(\hat{a}(z^{-1})) = na \\ rank(P_i(z^{-1})) = np \le na + ns' \\ rank(S'(z^{-1})) = ns' \\ rank(R(z^{-1})) = nr = na + ns' \end{cases} \tag{6}$$

Equation (5) can be written in the form of $\mathbf{Mx} = \mathbf{p}$, where $\mathbf{M}$ is the Sylvester matrix, with dimensions of $(na + ns^{'})\mathrm{x}(na + ns^{'})$, where:

$$\begin{cases} x^T \overset{\Delta}{=} [1 \quad s_1 \quad s_2 \quad \dots \quad s_{ns'} \quad , \quad r_0 \quad r_1 \quad \dots \quad r_{na+ns'-1}] \\ p^T \overset{\Delta}{=} [1 \quad p_1 \quad p_2 \quad \dots \quad p_{na+ns'-1}] \end{cases} \tag{7}$$

and $p_i$ are the coefficients of the characteristic polynomial $P_i(z^{-1})$ from (5). The solution for the polynomials from (5) is then obtained by inversion of matrix $M$ :

$$x = M^{-1} p \tag{8}$$

Polynomial $T(z^{-1})$ is calculated by imposing the specified condition that the global system structure of figure 2 has the same behavior as the set-point trajectory:

$$G^*_{RST}\left(z^{-1}\right) \overset{\text{def}}{=} \frac{\hat{b}_m\left(z^{-1}\right)}{\hat{a}_m\left(z^{-1}\right)} T\left(z^{-1}\right) G_{RS}\left(z^{-1}\right) = \frac{\hat{b}_m\left(z^{-1}\right)}{\hat{a}_m\left(z^{-1}\right)} \tag{9}$$

We have already established that:

$$G_{RS}\left(z^{-1}\right) = \frac{1}{P_i\left(z^{-1}\right)} \tag{20}$$

Which leads to the identification of $T(z^{-1})$ with $P_i$ : $T(z^{-1}) = P_i(z^{-1})$.

For the (FRC-1) system, a first-order model $(\hat{b}_1, \hat{a}_1)$ was evaluated based on the technological data acquired during the evolution of the process:

$$\begin{aligned} \hat{b}_1 &= 0.19033\, z^{-1} \\ \hat{a}_1 &= 1 - 0.90484\, z^{-1} \end{aligned} \tag{31}$$

and a digital polynomial algorithm RST ensuring independent dynamic performances on tracking and rejection of disturbances was computed:

$$\begin{aligned} R_1 &= 0.0956 - 0.856 z^{-1} \\ S_1 &= 0.4758 - 0.4758 z^{-1} \\ T_1 &= 1 - 1.809 z^{-1} + 0.819 z^{-2} \end{aligned} \tag{42}$$

The control algorithm was calculated using the pole placement method and the closed loop performances are presented in the Figure 3.

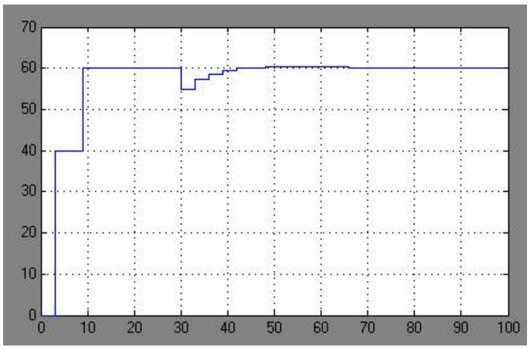


**Fig. 3.** FRC-1 performances.

For the (FRC-2) system, the $(\hat{b}_2, \hat{a}_2)$ model was estimated using the same procedure, obtaining the following results:

$$\begin{aligned} \hat{b}_2 &= 0.1903\,z^{-1} \\ \hat{a}_2 &= 1 - 0.904\,z^{-1} \end{aligned} \tag{53}$$

and the corresponding control algorithm:

$$\begin{aligned} R_2 &= 0.5907 - 0.4731\,z^{-1} \\ S_2 &= 0.1903 - 0.1903\,z^{-1} \\ T_2 &= 1 - 1.314094\,z^{-1} + 0.43171\,z^{-2} \end{aligned} \tag{64}$$

The closed loop system performances are illustrated in Figure 4.

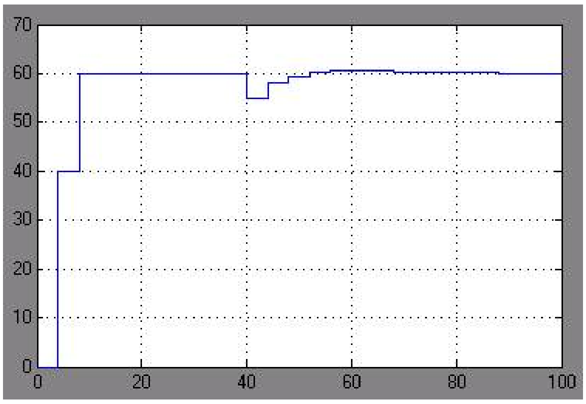


**Fig. 4.** FRC-2 performances.

To control the heating of air in a blast furnace, closed-loop systems are used: (FRC-3) for the flow that supplies the air heating system at the inlet of the blast furnace at a set-point of 50.000 m³/h and (TRC4) for the air temperature that complies with the set-point of 1200°C.

For the (FRC-3) system, the second-order model $(\hat{b}_3, \hat{a}_3)$ was estimated:

$$\hat{b}_3 = 0.06777z^{-1} + 0.05188\,z^{-2}$$
$$\hat{a}_3 = 1 - 1.3299z^{-1} + 4.49258\,z^{-2} \qquad (75)$$

and the corresponding digital algorithm:

$$R_3 = 8.35702 - 11.111503\,z^{-1} + 3.754475\,z^{-2}$$
$$S_3 = 1 - 0.5663\,z^{-1} - 0.4336z^{-2} \qquad (86)$$
$$T_3 = 8.35702 - 11.111503\,z^{-1} + 3.754475\,z^{-2}$$

The second-order dynamic model $(\hat{b}_4, \hat{a}_4)$ was evaluated and validated by an experimental identification operation (MCR) for the (TRC-4) system:

$$\hat{b}_4 = 0.00123 + 0.000139z^{-1}$$
$$\hat{a}_4 = 1 - 1.37198z^{-1} + 0.37623z^{-2} \qquad (97)$$

and the corresponding digital control algorithm:

$$R_4 = 1.76889 - 2.03422\,z^{-1} + 0.51875\,z^{-2}$$
$$S_4 = 0.00123 + 0.000605\,z^{-1} - 0.001643\,z^{-2} \qquad (108)$$
$$T_4 = 1 - 0.99317z^{-1} + 0.24660z^{-2}$$

which ensures the imposed performances was calculated [8, 9].

A designed module for control parameters and the dynamic performances are presented in the figure 5.

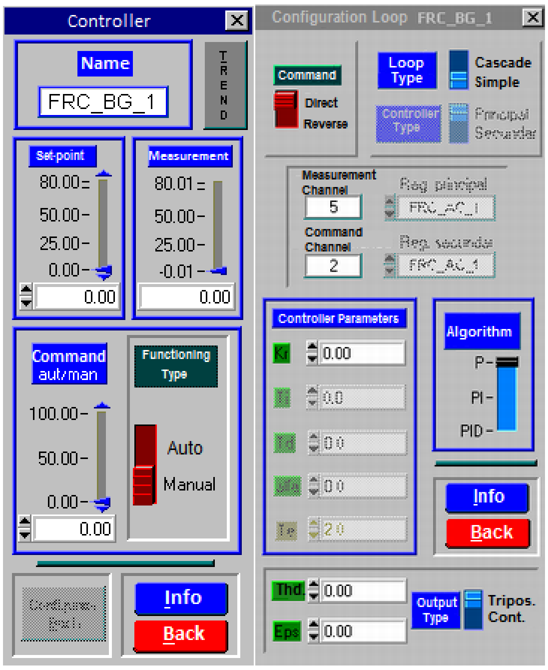


**Fig. 5.** Interface for control module of technological parameters.

Before implementing the designed systems, the (nominal) performances of the closed-loop systems were tested in simulation. Some improvements regarding the nominal system design using a robust strategy based on sensibility function to keep performance in real time were made [8, 9].

## 3. Combustion process optimization

In terms of optimization, at the supervisory level, a multivariable non-linear model of the combustion process was calculated. The output of this model is the concentration of oxygen in the residual combustion gas, which shows the quality of the combustion process. The inputs are the flow rate of the fuel mixture and the air flow rate for combustion.

The optimization problem was solved using the random search direct method COMPLEX [4, 5, 14].

The concentration of oxygen $z(\%O_2)$ was chosen as the quality variable (thus defining the optimization criterion), which depends on the inputs: combustion gas flow rate $y_1$ and the combustion air flow rate $y_2$.

The main idea is to find the optimal decision for the combustion process [17, 18] and to minimize the degree of environment pollution, respectively.

The optimal solution set $(y_1^*, y_2^*)$, is automatically taken as a set-points $(r_1^* = y_1^*, r_1^* = y_2^*)$ for the lower level, which leads the combustion process to the optimal point of operation through closed loop system (Figure 6).

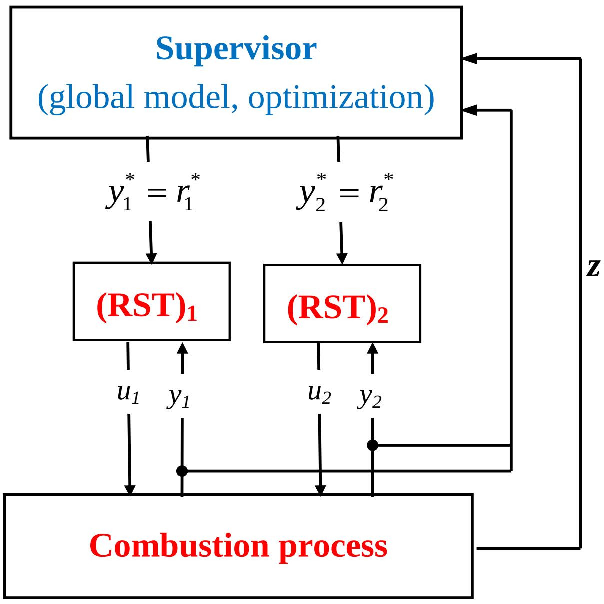


**Fig. 6.** Hierarchical control architecture.

The quasi-stationary decision model $\hat{z}(\%O_2) = f(y_1, y_2)$ was evaluated and, subsequently, the functions that express the technological constraints for concentration $\hat{z}_1$ of carbon monoxide, for temperature $\hat{z}_2$ of the cowper and temperature $\hat{z}_3$ of the residual gas, which all depend on the same variables $y_1$ and $y_2$ were identified:

$$\begin{aligned} \hat{z}_1(\%CO) &= f_1(y_1, y_2) \\ \hat{z}_2(T_{cowpercupola}) &= f_2(y_1, y_2) \\ \hat{z}_3(T_{flowgas}) &= f_3(y_1, y_2) \end{aligned} \tag{119}$$

These non-linear functions (models) were evaluated using the Least Squares experimental identification technique [4, 5, 15].

The experimental protocol concentrates on the data acquisition procedure during the first heating interval of the installation, with an imposed duration (resolution of 128 observations with a two-second acquisition period).

With the measurements collected in real time, the following models were estimated:

$$\begin{aligned} \hat{z} &= -9.665 + 0.229 y_1 - 0.0009 y_1^2 + 0.010 y_2 \\ \hat{z}_1 &= -4282.875 - 21.566 y_1 - 0.077 y_1^2 + 21.500 y_2 \\ \hat{z}_2 &= 1277.613 + 0.001 y_1^2 - 0.387 y_2 \\ \hat{z}_3 &= 499.161926 - 0.002147 y_1 - 3.49945 y_2 \end{aligned} \tag{20}$$

The first equation represents the combustion process model and the following: $\hat{z}_1$, $\hat{z}_2$, $\hat{z}_3$ - the models of the technological constraints of the process.

The optimization problem is expressed as a non-linear programming problem:

$$\min\{I = -9.665 + 0.229 y_1 - 0.0009 y_1^2 + 0.010 y_2\} \tag{212}$$

by respecting all the constraints:

$$\begin{aligned} &0 \le \hat{z}_1 \le 450\, ppm \\ &0 \le \hat{z}_2 \le 1300^0 C \\ &0 \le \hat{z}_3 \le 340^0 C \\ &96.309 \le y_1 \le 102.452 \\ &46.602 \le y_2 \le 57.992 \end{aligned} \tag{22}$$

The solution to this problem, which is calculated using an optimization technique that uses the search direct digital method COMPLEX, represents the optimal operation point of the combustion process:

$$y_1^* = 97469.85 m^3 / h$$
$$y_2^* = 47804.16 m^3 / h \quad (23)$$

Where $y_1^*$ represents the optimal flow of combustible gas and $y_2^*$ - the optimal flow of combustion air.

This operating point will guarantee the following minimum value of oxygen in the residual gas:

$$z_{\min}^*(\%O_2) = 4.65\% \quad (24)$$

Using the approach presented in our work, methane fuel consumption was reduced by $7.41\%$ from the average level of consumption and the limit of constrains for carbon monoxide of $450\, ppm$, was respected.

The values of the constraint variables calculated at this operating point are as follows:

$$\overset{*}{z}_1\left(\%CO\right) = 415.73\, ppm$$
$$\overset{*}{z}_2\left(T_{cupola}\right) = 1273.25^o C \quad (25)$$
$$\overset{*}{z}_3\left(T_{flowgas}\right) = 311.47^o C$$

The optimal decision $(y_1^*, y_2^*)$ is automatically taken as a set-point $(r_1^* = y_1^*, r_1^* = y_2^*)$ for the lower level, which leads the combustion process to the optimal point of operation through closed loop systems.

The optimization problem (21)-(22) is reconstructed and solved once the model $\hat{z}$ is necessarily updated based on the movement of the process operating point. This application has been put into place and it controls a blast furnace heating setup on a steel plant from Galati (Romania), recognized in South-Eastern Europe [8, 9].

## Conclusions

An adequate solution for air heating installations which aliment the blast furnaces were designed and implemented. This solution ensures efficient treatment for heating the air of the steel plant and optimizes the combustion process, an important supplier of the required energy and a recognized industrial source of pollution.

The proposed control structure for the air heating process was organized across two interconnected levels in a hierarchical configuration: the execution level whose purpose is to control the key parameters of the combustion process and the heating air process and the supervision level whose purpose is to optimize the combustion process, necessary for heating the air and for minimizing the degree of environment pollution.

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