MULTIVARIABLE CONTROL OF A REDUCTION FURNACE

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Abstract: In the world of control the enormous difficulties encountered in reaching satisfactory results with the design and implementation of controllers for Multi-Input/Multi-Output (MIMO) processes are well known, in particular; when the interactions can not be ignored. This situation becomes even more complicated when the control process exhibits non-linear and/or time-varying dynamic characteristics. Not uncommonly, system designers of industrial processes control have to face such complexities. This paper describes the experience attained by the authors in the design of a fuzzy control system for a reduction furnace in a nickel processing plant, which exhibits the above mentioned characteristics. *Copyright © 2007 IFAC.*

Keywords: Fuzzy control, fuzzy controller, reduction, multihearth furnace, multivariable systems

1. INTRODUCTION

The process taking place in a multihearth roasting furnace is one of the more important stages of the ammonium carbonate technology for the extraction of nickel from lateritic ores, since the quantity of the obtained nickel sinter greatly depends on the efficient development of the reduction. The purpose of the reduction process is to maximise the transformation of both nickel and cobalt to a zero valence state, while minimising the reduction of the iron. For a good reduction process two premises must be accomplished: a suitable temperature profile inside the furnace and an appropriate reductant atmosphere for the development of chemical reduction reactions.

Complex physical and chemical processes such as those mentioned above (multiple inputs and outputs, interactions, non-linearities) occur in the roaster. Several previous attempts to implementing control systems on this furnace, using classical design strategies, have not been successful, although these works were carried out by well known and experienced companies, dedicated to the development of instrumentation and control. For this reason, the possible use of Artificial Intelligence techniques was evaluated by the authors for the controller's design, keeping in mind that the control of the operation is traditionally carried out by human operators, based on their experience and their ability, while taking into account the historical records of the process behaviour.

Fuzzy logic is one of the paradigms of Artificial Intelligence that has fully proven its potential to provide effective solutions to the problem of control of complex processes such as the one treated in this paper.

In this work, the control of a sub process which is critical for the efficient operation of the furnace, (the so-called post combustion, comprising hearths 4 and 6) is approached. Reported experiments, (Selva, 1984), have demonstrated that the temperature stability in hearth 4 significantly influences the thermal stability of the furnace, while the existence of temperature values below the established ones causes a shift of the thermal zones of the furnace, resulting in a decrease in the yield of nickel and cobalt extraction. On the other hand, the appropriate control of the temperature in the mentioned hearths highly contributes to a decrease in the environmental pollution taking place at the expulsion of CO and H_2 components to the ecosystem.

The objective of this paper is to present the preliminary results obtained in the design of a control system for the post combustion sub process of the reduction furnace using fuzzy logic.

2. DESCRIPTION OF THE PROCESS

The dried milled ore is heated in a reducing atmosphere in a Herreshoff roaster, 21,3*m* high and 6,7*m* in diameter, containing 17 bricked hearths. The reduction of the nickel and cobalt minerals in the ore is achieved by a combination of the addition of fuel oil to the ore feed and operation of the oil fired combustion chambers with sub-stoichiometric air, in order to supply a roaster atmosphere which contains hydrogen and carbon monoxide. Selective reduction of nickel is beneficial for the extraction process. Therefore, good control of the roasting conditions is essential for optimal nickel recovery in the process (Habashi, 1997).

The ore is heated, dehydrated and partially calcined in the top hearths and then reduced as it proceeds down through the roaster. The reduced calcine exits at the bottom; afterwards it is cooled, and then quenched in liquor coming from the leaching step. A cyclone and an electrostatic precipitator collect the dust carried in the exhaust gases.

The roaster atmosphere contains approximately 10% CO and 10% H_2. To recover most of the chemical heat value of the reducing gases, before they are vented out to the atmosphere, both CO and H_2 are combusted by the addition of air at the hearths 4 and 6, since

$$\begin{aligned} 2CO + O_2 &\rightarrow 2CO_2 + \Delta \\ 2H_2 + O_2 &\rightarrow 2H_2O + \Delta \end{aligned} \qquad (1)$$

This would give better control of the temperature profile while maintaining potential extraction and preserving the mechanical integrity of the roaster.

If the quantity of reductants changes irregularly, the steady state relationship between the temperature in the hearth 4 (H4) and the air flow is strongly non linear, as shown in Figure 1. Clearly, two main regions of operation can be distinguished with positive (for low air flow rate) and negative gain (for higher air flows).

The process was approached as a multivariable system, keeping in mind the output variables of interest and those that can be used for the control (manipulated variables). Thus, the system can be considered as a black box whose variables are (see Figure 2):

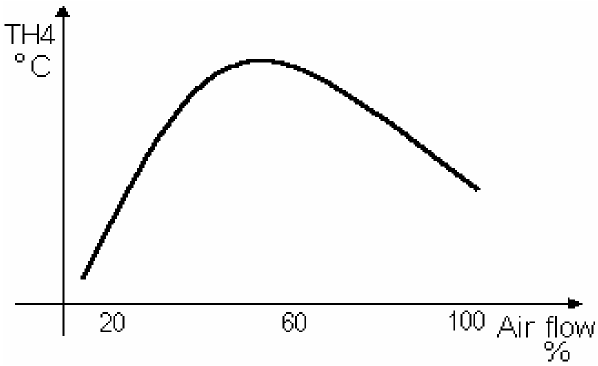

Fig. 1. Steady-state relationship between the temperature and the air flow in H4.

Manipulated (control) variables,

FaH4: Air flow to hearth 4
FaH6: Air flow to hearth 6
Fp: Fuel oil flow to combustion chambers
Fm: Ore flow fed to the roaster

Output (controlled) variables,

TH4: Temperature of the hearth 4
TH6: Temperature of the hearth 6

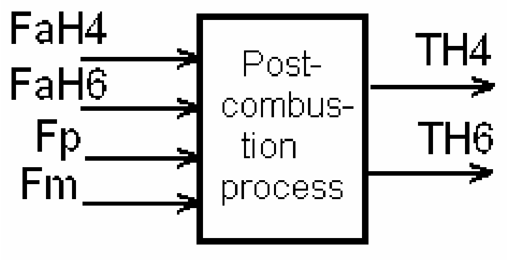

Fig. 2. Post-combustion process viewed as a "black box".

In order to build up a simulation environment to test the control structures, a set of simple linear low order models of the process have been obtained. The experimental identification was carried out by applying pseudo random binary sequences (PRBS) in the four inputs. The two outputs were registered and a first (or second) order plus delay model was tuned for the eight transfer functions. The experiments were repeated in both operating modes, with positive and negative static gain, showing the different behaviour of the process.

Following the standard parameter estimation techniques (Ljung, 1999), the elements of the two transfer matrices were obtained from the "noisy" response to the PRBS excitation. The transfer functions are shown in Tables 1 and 2. They correspond to the operating regions with positive and negative gain respectively.

Table 1 Transfer function matrix for the positive gain zone

$$\frac{TH4}{FaH4}=\frac{-0.0015(s-0.79)}{(s+0.025)(s+0.019)}$$
$$\frac{TH4}{FaH6}=\frac{-0.0074(s+0.22)}{(s+0.05)(s+0.0028)}$$
$$\frac{TH4}{Fp}=\frac{0.041}{(s+0.013)}$$
$$\frac{TH4}{Fm}=\frac{-0.084e^{-360s}}{(s+0.002)}$$

$$\frac{TH6}{FaH4}=\frac{0.00018(s-0.013)}{(s+0.018)(s+0.00014)}$$
$$\frac{TH6}{FaH6}=\frac{-0.0021(s-0.63)}{(s+0.032)(s+0.0042)}$$
$$\frac{TH6}{Fp}=\frac{0.0098(s+0.0042)}{(s^2+0.028s+0.00036)}$$
$$\frac{TH6}{Fm}=\frac{-0.0046(s+0.019)e^{-420s}}{s^2+0.0021s+0.00058}$$

Table 2 Transfer function matrix for the nagative gain zone

$$\frac{TH4}{FaH4}=\frac{0.0024(s-0.53)}{(s+0.033)(s+0.0039)}$$
$$\frac{TH4}{FaH6}=\frac{0.0088(s+0.26)}{(s+0.22)(s+0.0022)}$$
$$\frac{TH4}{Fp}=\frac{0.041}{(s+0.013)}$$
$$\frac{TH4}{Fm}=\frac{-0.084e^{-360s}}{(s+0.002)}$$

$$\frac{TH6}{FaH4}=\frac{-0.00013(s-0.03)}{(s+0.01)(s+0.0021)}$$
$$\frac{TH6}{FaH6}=\frac{-0.0046(s+0.27)}{(s+0.17)(s+0.0024)}$$
$$\frac{TH6}{Fp}=\frac{0.0098(s+0.0042)}{(s^2+0.028s+0.00036)}$$
$$\frac{TH6}{Fm}=\frac{-0.0046(s+0.019)e^{-420s}}{s^2+0.0021s+0.00058}$$

3. STRUCTURE OF THE CONTROLLER

In designing the multivariable fuzzy logic controller, see (Viljamaa, 1995), a Mamdani-type inference system was used. The controller has five input variables: the error (e) and change of the error (ce) of temperatures, *TH4* and *TH6*, and the specific fuel consumption. Those variables were defined as $e(k)=r(k)-y(k)$ and $ce(k)=e(k)-e(k-1)$, respectively, where r is the reference signal, y is the output and k is the discrete time.

The specific fuel consumption is given by the weight in kilograms of petroleum per one ton of nickel fed to the furnace. The output variables (manipulated variables, u) are the change in *FaH4*, *FaH6*, *Fp* and *Fm*. The control is incremental so that the final control signals sent to the system are calculated by

$$u(k)=u(k-1)+\Delta u(k)$$

Trapezoidal membership functions were used for the partition of the universes of discourse of all variables. The error, the specific consumption, the change in *Fp* and the change in *Fm* have three fuzzy subsets, the change of the error two fuzzy subsets and the change in

FaH4 and *FaH6* five subsets. Each rule base is composed of 108 rules.
The compositional operator sup-min and, for the defuzzification, the centroid method were used, see (Jager, 1995). The knowledge bases were created, basically, from the process's experienced operators and other engineering criteria. The software Matlab™ and its "Fuzzy Logic Toolbox" were used.

For roasting control purposes, the measurement of the temperatures is good enough, not being necessary the measurement of the carbon monoxide content in the exhaust gases, requiring much more expensive instrumentation. Nevertheless, as this device is available in our plant and in order to detect the process operating regions, the carbon monoxide content of exhaust gases will be used as an auxiliary process variable. This will allow a smooth control transfer between regions.

In order to better decouple both controlled variables, further investigations in the operators' behavior should be done to extract additional rules.

4. SIMULATION

The scheme of the simulated control system is shown in Figure 3.

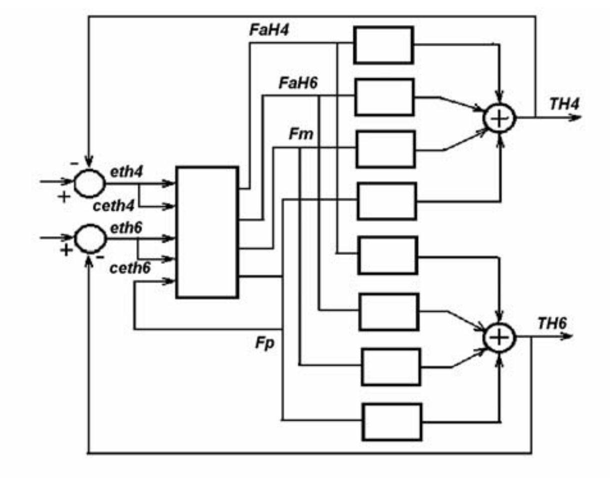

Fig. 3. Scheme of the simulated control system.

The goal of the experiments carried out by controlling the simulated system was to analyse the appropriateness of the designed fuzzy controller, obtaining preliminary conclusions before its implementation in the plant. Next, some simulation results are shown.

In the case of a multivariable process the controller's design should be carried out in such way that the interactions of the process are carefully considered. In our case, this interaction was intrinsically considered in the rule base extracted from the operators' knowledge.

The closed-loop response of the controlled simulated system operating in the positive gain zone, when changes in step of 20 ºC take place in the reference temperature of both hearths H4 and H6, can be observed in Fig. 4.

As the initial conditions do not correspond with those of a steady-state behaviour (the air input flows are not well tuned) there is an initial transient in both temperatures. Also, some transient interaction remains between the controlled variables, but they are decoupled in steady-state.

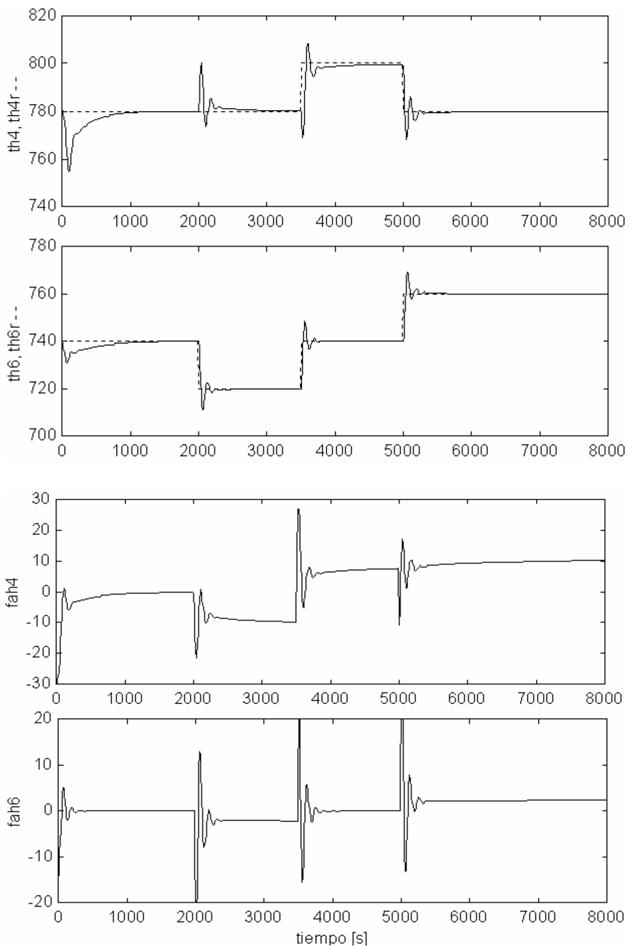

Fig. 4 Response of the controlled system operating in the positive gain zone. Steps in the reference of both controlled variables (Th4 and Th6) are applied.

The robustness of the behavior of the fuzzy controlled multivariable plant was experimentally investigated by realising the influence of the variations in the parameters of the system on the controlled plant responses. The changes in transfer function parameters can happen due to the diversity of the nickel concentration in minerals, which behave differently.

As an example, the responses obtained to changes in 200% of the gain in stationary state, for the transfer functions TH4/FaH4 and TH6/FaH6 are shown in Fig. 5. This test was carried when operating in the positive gain zone.

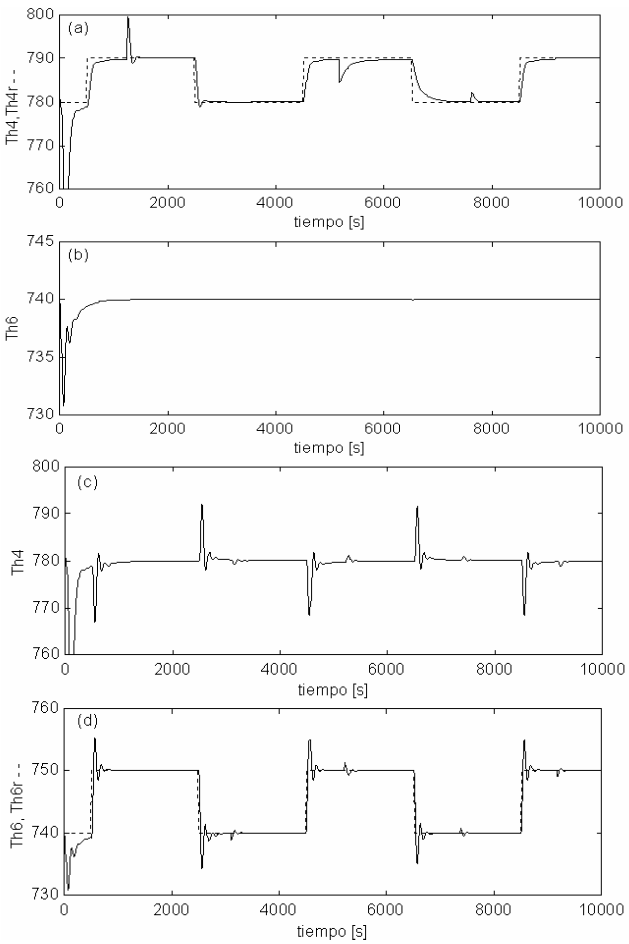

Fig. 5. Step responses under changes in the gains of the transfer functions *TH4/FaH4* and *TH6/FaH4*.

In Fig. 5 (a) and (b) the responses of Th4 and Th6 are shown respectively when a sequence of steps is applied in the reference of Th4. In the interval between 1000 and 2000 *s* the gain of TH4/FaH4 was doubled and between 3000 and 4000 *s* it was returned to its initial value; later on, from 5000 to 6000 *s*, it was reduced to half and finally between 7000 and 8000 *s* it was recovered the original value. The response of TH6 is practically unaffected.

In Fig. 5 (c) and (d) the responses of TH4 and TH6 are shown respectively when a sequence of steps is applied in the reference of Th6; between the 3000 and 4000 *s* the gain of TH6/FaH4 was doubled and between the 5000 and 6000 *s* it was returned to the initial value; later on, from 7000 to 8000 *s* it was reduced to half and finally between 9000 and 10000 *s* the original value is recovered. Here the effect of the interaction is evidenced. However, decoupling properties of the controller do not deteriorate significantly when large changes are made in the gain of the system. As already mentioned, additional rules should be extracted from the operators' behavior in order to better decouple both controlled variables.

In all the experiments carried out, the controlled variables time response exhibit appropriate settling time, the overshoot did not exceed the permissible limits: TH4(750 - 850), TH6(710 - 780) and show a negligible offset, for different external and internal disturbances.

It should be noted that the used signals are noise free. Thus, noise effect should be considered when implementing the new control structure in the plant, based on the sensors characteristics.

In these experiments, the transfer between operating modes has not been considered. For that purpose, the approach we are implementing is similar to that reported in (Ramirez, 2006), where local PID controllers were adapted (using a gain scheduling scheme) based on a driven variable. In our case, the driving signal will be the carbon monoxide content in the exhaust gases, strongly connected to the operating behaviour shown in Fig. 1. The fuzzy controllers will be easily integrated to provide a combined control action.

5. CONCLUSIONS

The results reached during the simulation stage were excellent, first it was verified that the decoupling properties of the designed multivariable controller are good and therefore it is able to minimize in an acceptable way the interactions among the controlled variables. In the experiments where changes took place in the disturbances the behavior of the system it was very good, still when these were quite drastic. In those where changes in the parameters of the system were carried out (gains, time constant and delays) it was broadly demonstrated the controller's robustness.

In general after any change carried out the error in stationary state was zero with appropriate settling time, while the overshoots for Th4 did not exceed 2% and for Th6 they did not exceed 1%. Keeping in mind all that outlined previously is considered that it is feasible the implementation in real time of the algorithm of designed control.

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