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EXPERIMENTAL CONTROL OF A CUPOLA FURNACE

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Abstract

In this paper we present some final results from a research project focused on introducing automatic control to the operation of cupola iron furnaces. The main aim of this research is to improve the operational efficiency and performance of the cupola furnace, an important foundry process used to melt iron. Previous papers have described the development of appropriate control system architectures for the cupola. In this paper experimental data is used to calibrate the model, which is taken as a first-order multivariable system with time delay. Then relative gain analysis is used to select loop pairings to be used in a multiloop controller. The resulting controller pairs meltrate with blast volume, iron temperature with oxygen addition, and carbon composition with metal-to-coke ratio. Special (nonlinear) filters are used to compute meltrate from actual scale readings of the amount of iron produced and to smooth the temperature measurement. The temperature and meltrate loops use single-loop PI control. The composition loop uses a Smith predictor to discount the deadtime associated with mass transport through the furnace. Experiments conducted at the Department of Energy Albany Research Center's experimental research cupola validate the conceptual controller design and provide proof-of-concept of the idea of controlling a foundry cupola.

1 Introduction

The cupola furnace is one of the primary foundry processes used to melt iron. A cupola is usually constructed as a water-cooled vertical cylinder. The cupola is charged at the top with fuel (usually coke) and metal (pig iron, scrap metal, cast iron scrap, foundry return scrap, and ferro-alloys). Air is injected into the cupola through tuyeres located near the bottom of the furnace, above the molten iron. The blast air is often heated and enriched with oxygen. As the coke is consumed the charge drops and melts, producing a continuous flow of molten iron (large cupolas may produce up to 100 tons/hour of hot iron). Key operational goals in cupola operation are to keep the iron properties within a prescribed range and, in some cases, to maintain a desired production rate. These goals are usually accomplished through judicious choice of the manipulated process variables, notably the blast properties (rate, temperature, and oxygen enrichment) and the charge composition (including coke-to-metal ratio, iron-to-steel ratio, and alloys).

Although the cupola remains the primary method for melting iron, especially for high-volume production, beginning in the 1950's various pressures led to a general decline in the domestic foundry industry. Recently the foundry industry has begun to regain its position in the world market. One thrust has been on improved understanding of the cupola process via a modeling effort [1]. Another thrust has been on improved operation of the cupola through automatic control technology. Cupola operation has not been greatly improved over the years and has always relied on the experience of the operator in deciding which process parameters to adjust to obtain the desired molten iron properties. In a recent study, it was found that foreign foundries have better trained operators [2]. These observations motivated a project funded by the Department of Energy (DOE) and the American Foundrymen's Society (AFS) aimed at demonstrating the feasibility of using feedback control technology to help achieve better operation of the cupola furnace with less dependence on the experience and skills of a single operator [3].

The DOE-AFS project team included the Idaho National Engineering and Environmental Laboratory (INEEL), a DOE national lab, Idaho State University (ISU), researchers at the DOE Albany Research Center (ALRC), and an industrial oversight committee sponsored by AFS. An experimental research cupola (an eighteen inch diameter furnace with a nominal meltrate of approximately two tons/hour) was designed, constructed, and instrumented at ALRC [4]. INEEL researchers developed a LabView-based computer instrument panel for data

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acquisition and control interfacing [5,6]. INEEL also developed a neural network model of the steady-state cupola [6,7]. ISU-developed control concepts for the furnace. The controller architecture has a hierarchical structure that includes system-level coordination for optimization and setpoint selection and process-level control for setpoint regulation [8].

In this paper we present some of the final process-level results from the DOE-AFS project. First, experimental data is used to define a first-order multivariable system with time delay. This model suggests that a multiloop control strategy is sufficient for the ALRC cupola. Next, relative gain analysis is used to select loop pairings to be used in a multiloop controller. Controllers are then defined based on the suggested pairings. The resulting controller pairs meltrate with blast volume, iron temperature with oxygen addition, and carbon composition with metal-to-coke ratio. The temperature and meltrate loops use single-loop PI control. The composition loop uses a Smith predictor to handle the significant time delay associated with the movement of the charge down the furnace. We also describe special filters that are used to compute meltrate from actual scale readings of the amount of iron produced and to smooth the temperature measurement. Finally, we present experimental results that validate the conceptual controller design and provide proof-of-concept of the idea of controlling a foundry cupola.

2 A Model of the Cupola

The cupola is a very complex dynamical system. Unfortunately, to date there is not a complete first-principles model of the cupola available. Accurate modeling of the process requires careful consideration of chemical and physical principles. Indeed, the most comprehensive model available, the AFS model mentioned above, is only a one-dimensional steady-state model and even so, involves well over forty coupled non-linear differential equations (in space) as well as numerous algebraic relations representing stochiometric and other relations. However, in order to design a controller for the furnace it is desirable to have a simple model that retains the main physical characteristics of the cupola. For this reason a first-order multivariable model is used in the controller design.

2.1 Manipulated and Controlled Variable Selection

Based on preliminary analysis of the cupola process, information gathered from industrial cupola operators, and constraints placed by the actual instrumentation capabilities, manipulated and controlled variables were chosen in the following way:

1. *Manipulated variables (process inputs):*

   (a) Coke-to-metal ratio (CMR)
   (b) Oxygen enrichment (O_2)
   (c) Blast rate (B_R)

2. *Controlled variables (process outputs):*

   (a) Iron carbon content (%C)
   (b) Iron temperature (T_{FE})
   (c) Melt rate (MR)

Although other choices of inputs and outputs could be made, such as various types of metal input streams, concentrations of other elements such as S, Si, or Mn, or off-gas measurements, a decision was made to limit the scope of the proof-of-concept experiments to the fundamental signals of interest. Future activity is planned to expand the number of signals used in the controller.

2.2 Transient Model

A number of transient response tests were conducted in order to build an approximate model of the system. Because the furnace is expensive to operate the typical procedure was to combine transient response tests with control tests. First the furnace would be started and brought to steady-state. Then a step change would be made to one of the inputs. After the furnace had settled it would be returned to its initial setting. While this was taking place steady-state gains and time constants would be computed and controller gains would be selected. Then, during the final part of the run, the controller would attempt to regulate the furnace to a new setpoint. Six experimental runs of this nature were executed using only blast rate and oxygen enrichment. Two other runs were performed to study the transients associated with changes in coke-to-metal ratio. All tests were conducted starting from the same nominal operating point (blast rate of 300 scfm, no oxygen enrichment, and 12% coke-to-metal ratio). From these eight tests a transient model was developed. This model was used to design the controllers used in the final experiment described below.

As we have noted, the transient model is a first-order multivariable system with time-delay. The transfer matrix derived from the transient tests is given by:

$$\begin{bmatrix} \Delta \%C \\ \Delta T_{FE} \\ \Delta MR \end{bmatrix} = \begin{bmatrix} \frac{0.04e^{-Ts}}{300s+1} & \frac{0.03}{300s+1} & 0 \\ \frac{4e^{-Ts}}{300s+1} & \frac{12}{300s+1} & 0 \\ \frac{0.04e^{-Ts}}{300s+1} & \frac{2}{300s+1} & \frac{0.08}{60s+1} \end{bmatrix} \begin{bmatrix} \Delta CMR \\ \Delta O_2 \\ \Delta B_R \end{bmatrix}$$

The time delay T was determined to be one hour, or 3600 seconds. Notice that this is much longer than the five minute time constant seen in most entries. Also note that we have expressed the model in terms of deviations from nominal.

3 Controller Design

3.1 Controller Structure

It is clear from the dynamic model that one of the inputs, the coke-to-metal ratio, is delayed, while the other two, the oxygen enrichment and the blast rate, are undelayed. These points were understood to be true in the early stages of the project. Consequently, we initially designed controllers based on these observation and on steady-state assumptions about the process obtained from analysis of the AFS model. These designs are described in [9] and [10]. In these earlier works it was assumed that the carbon content would be affected only by the CMR while the iron temperature and the melt rate would be affected by each of the three inputs. The design of the control system could be greatly simplified if the effect of the delayed and undelayed inputs are completely decoupled. Thus, the proposed control system architecture for the cupola, described in [10] had three key parts:

1. A feed forward controller – decouples the delayed and undelayed parts of the dynamical model.
2. Coke-to-metal ratio (CMR) controller – required to work with a long uncertain time delay. This controller was proposed to be a Smith predictor with a robust controller to handle uncertainty in the time delay.
3. Oxygen (O_2) and blast rate (B_R) controllers – acts with no-delay. These were proposed to be multivariable PI controllers designed using an LQR procedure.

However, after the experimental dynamic model was available a decision was made to use a simpler overall approach during the implementation. First, because the delay time associated with the charge input is so much longer than the time constants of the system, it seems that the decoupling of the delayed input from the temperature and meltrate is not really necessary. Also, it can be seen that there is quite a bit of natural decoupling inherent in the system. In particular, because the dynamics associated with the blast rate input are faster than those associated with oxygen and because blast rate has no effect on temperature in the ALRC cupola, it seems that there is no real need for a multivariable controller associated with the undelayed inputs. These observations led us to implement a multiloop control strategy. Although we retained the Smith predictor, we did not keep any feedforward elements. Also, because of the first-order nature of all the transfer matrix entries, we used simple PI controllers.

3.2 Input-Output Pairing Analysis

To implement a multiloop controller it is necessary to decide which input should be paired with which outputs. Although we might observe that coke-to-metal ratio is an obvious candidate for pairing with the percent carbon in the iron, it is useful to consider the issue more systematically. A tool commonly used in the process control community is the so-called relative gain analysis, which is based on the steady-state gain matrix, which we denote K_{ss}. The relative gain matrix, R, is computed as

$$R = K_{ss} .* \left(K_{ss}^{-1}\right)^T$$

where ".*" denotes entry-by-entry multiplication. The entries of the relative gain array matrix provide a measure of the effect of interaction in a multiloop control system. It can be shown that one should use loop pairings that have relative gain array entries that are positive and close to unity.

For the ALRC cupola the steady-state gain matrix is defined by

$$\begin{bmatrix} \Delta\%C \\ \Delta T_{FE} \\ \Delta MR \end{bmatrix} = \begin{bmatrix} 0.04 & 0.03 & 0 \\ 4 & 12 & 0 \\ -2 & 2 & .08 \end{bmatrix} \begin{bmatrix} \Delta CMR \\ \Delta O_2 \\ \Delta B_R \end{bmatrix}$$

From this we can compute the relative gain array matrix:

$$R = \begin{bmatrix} 1.3 & -.3 & 0 \\ -.3 & 1.3 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

This matrix makes it clear that, from the perspective of loop gain interactions, the following loop pairings should be used:

1. %Carbon controlled using coke-to-metal ratio.
2. Temperature controlled using oxygen.
3. Meltrate controlled using blast.

3.3 Controller Implementation

Using the input-output pairings given above, we end up with the control system block diagram shown in Figure 1. The Smith predictor structure is standard and uses a PI controller (this is indicated by the letters "PID" in the block denoted "Smith predictor" in the figure). All controllers shown in the figure were implemented digitally, using LabView. Four points should be noted:

1. The control system is actually a cascade controller, where the controllers we have described here are actually used to drive the setpoints for the instrument-level controllers. The one exception to this is the coke-to-metal ratio. This loop was implemented in a semi-automatic fashion as follows. The controller took measurements from the data acquisition portion of the LabView system and computed the appropriate changes to the coke-to-metal ratio. These

changes were displayed on the monitor and were then relayed via two-way radio to personnel charging the cupola.

2. Due to hardware and data acquisition constraints there were a number of different sampling times in the actual implementation. These are also indicated in Figure 1.

3. All of the key output signals suffered from noise problems. As a result, it was necessary to use various filters in the control system. For %Carbon and temperature the filters were simple averaging filters. For temperature we averaged and also applied hardlimiters and standard deviation filters to reject measurements that were too far out of range to be true. This was necessary because we were using an unreliable pyrometer to measure the temperature of the molten iron. Getting a good meltrate measurement was a more challenging problem. This was because the only available measurement was the actually weight of iron. Thus it was necessary to differentiate the measurement of weight to get meltrate (weight per unit time). The technique used to do this was to compute a least-squares fit of a line to a fixed number of weight readings. The slope of this line, which was also passed through hardlimiters and standard deviation filters, is the meltrate. A more complete description of the various signal filters will be included in the final version of the paper.

4. Actual controller gains were chosen via simulation. Closed-loop poles were chosen so that there was no overshoot in any signals in the simulated experiments. This was done using standard root locus-based design and then checked via simulation. The resulting controller had the form:

$$\begin{bmatrix} \Delta CMR \\ \Delta O_2 \\ \Delta B_R \end{bmatrix} = \begin{bmatrix} C_1(s) & 0 & 0 \\ 0 & C_2(s) & 0 \\ 0 & 0 & C_3(s) \end{bmatrix} \begin{bmatrix} E_{\%C} \\ E_{T_{FE}} \\ E_{MR} \end{bmatrix}$$

where E denotes the error signal. The Smith predictor used to regulate carbon concentration has the form:

$$C_1(s) = \frac{C(s)}{1 + C(s)G(s)(1 - e^{-Ts})}$$

where

$$C(s) = 0.1 + \frac{0.03}{s}$$

$$G(s) = \frac{0.04}{300s + 1}$$

The other two controllers are given by:

$$C_2(s) = 0.1 + \frac{2.8 \times 10^{-4}}{s}$$

$$C_3(s) = 3.0 + \frac{0.03}{s}$$

4 Experimental Results

As noted, a number of experiments were conducted. We began with single-loop control of meltrate and temperature, one at a time. A representative result is shown in Figure 2, which gives the output response of an experiment to control meltrate by adjusting the blast input. The setpoint in this experiment was 45 lbs/min. Notice that the meltrate shows significant variation about the setpoint. Analysis has shown that this variation is real and reflects how hard it is to control the cupola. After completing a number of single-loop experiments, we demonstrated multiloop control of meltrate and temperature simultaneously. We then conducted a single-loop control experiment to regulate the carbon concentration using the Smith predictor. The final experiment consisted of demonstrating simultaneous control of all three outputs of interest: meltrate, temperature, and percent carbon. In the interest of space we will only discuss the final experiment. The sequence of events was as follows:

1. The furnace was started and brought to steady-state.
2. The controllers were turned on.
   Meltrate setpoint was 40 lbs/min.
   Iron temperature setpoint was 1400 degrees C.
   %Carbon setpoint was 3.3%.
3. After about three hours the meltrate setpoint was changed to 35 lbs/min.

Figure 3 shows the results of the experiment. The plots on the left are the manipulated variables and the plots on the right are the respective controlled variables that are paired with each manipulated variable. It is clear that the controller is effective in driving the system to the desired setpoints.

5 Conclusion

In this paper we have presented experimental results that demonstrate the feasibility of using automatic control to regulate primary process variables in the foundry cupola. In future work these ideas will be incorporate into an integrated intelligent measurement and control system. It is expected that application of these ideas in an industrial setting will result in significant operational benefits.

6 References

[1] E.D. Larsen, D.E. Clark, H.B. Smartt, K.L. Moore, "Intelligent Control of Cupola Melting," *Transactions of the American Foundrymen's Society*, 95-67, pp 215-219, 1995.

[2] Midland–Ross Corporation, Surface Combustion Division, "Foundry Industry Scoping Study—A Review of the U.S. Ferrous Foundry Industry Electro-Technology Applications," Technical Report, CMP Report No. 86–6, Elgin AFB, November 1986.

[3] K. Moore, "Intelligent Cupola Control," Funded Research Program, U.S. Dept. of Energy Metal Casting Competitiveness Initiative, Idaho Field Office, Idaho Falls, ID, October 1994.

[4] P.E. King, L.G. Higgins, V. Stanek, E.D. Larsen, D.E. Clark, K. L. Moore, "AFS Cupola Model Verification, Part I - Initial Investigations," presented at the 1997 AFS Casting Congress, Seattle, WA, April 1997.

[5] E.D. Larsen, D.E. Clark, H.B. Smartt, K.L. Moore, "Advanced User Interfaces and Intelligent Control," in *Proceedings of the 1994 INEL Technical Computing Symposium*, Idaho Falls, ID, October 1994.

[6] E.D. Larsen, D.E. Clark, K.L. Moore, V. Stanek, P.E. King, "Neural Network Applications for Cupola Melting" in *Materials Processing in the Computer Age, Proceedings of the 1995 TMS Annual Meeting*, Las Vegas, NV, February 1995.

[7] E.D. Larsen, D.E. Clark, H.B. Smartt, K.L. Moore, P. E. King, "Advanced Control of Cupola Melting" in *Proceedings of Technology 2004, the 5th National Technology Transfer Conference and Expo*, Washington, DC, November 1994.

[8] E.D. Larsen, D.E. Clark, K.L. Moore, P.E. King, "Intelligent Control of a Cupola Furnace," in *Proceedings of Technology 2006, the 6th National Technology Transfer Conference and Expo*, Anaheim, CA, October 1996.

[9] K. L. Moore, M. A. Abdelrahman, D. Clark, E. Larsen, H. Smartt, and C. Einerson, "A Multivariable Smith Predictor for Intelligent Control of a Cupola Furnace," In *Proceedings of the American Control Conference*, Seattle, Washington, June 21–23, 1995.

[10] M. A. Abdelrahman, K.L. Moore, "Robust Control of Cupola Iron Furnaces," in *Proceedings of the 1996 American Control Conference*, Albuquerque, NM, June, 1996.

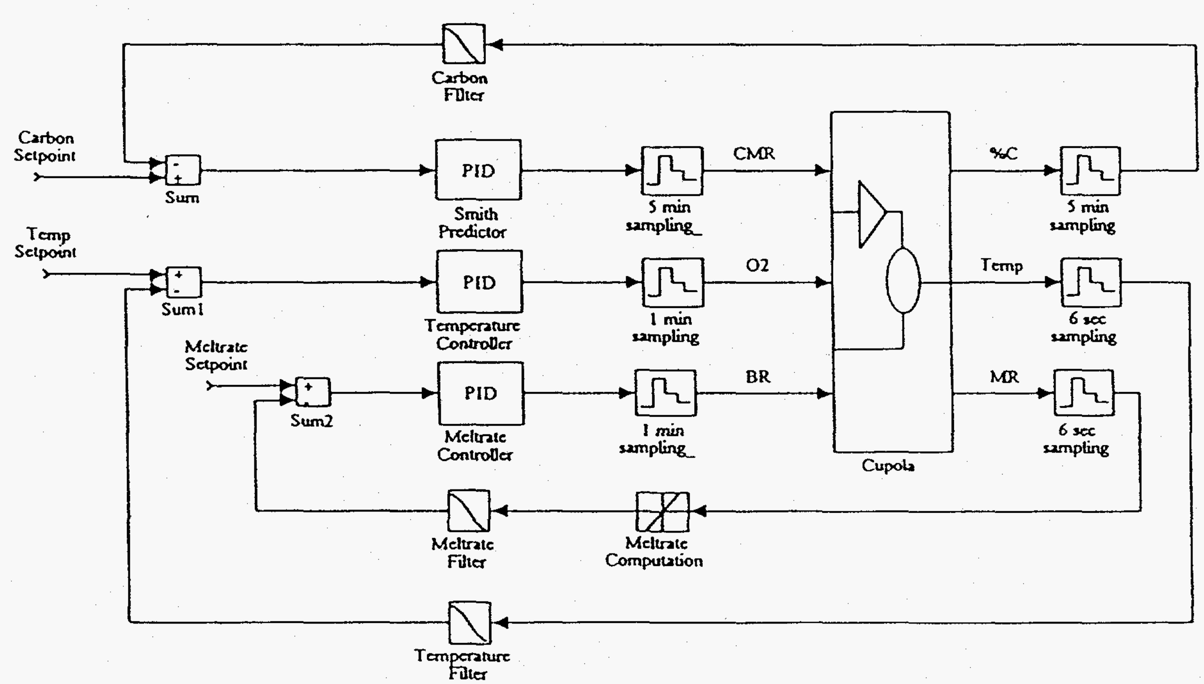

Figure 1: Controller configuration

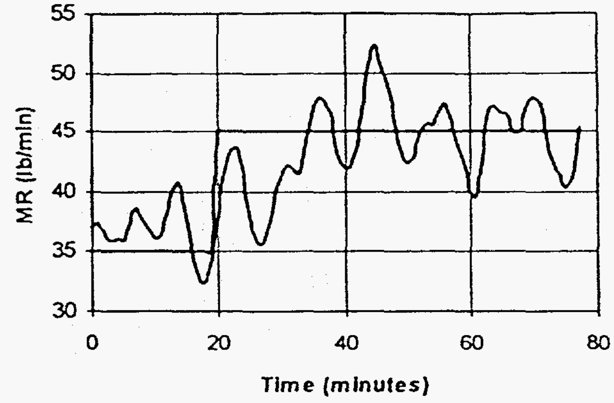

Figure 2: Single-loop control of meltrate..

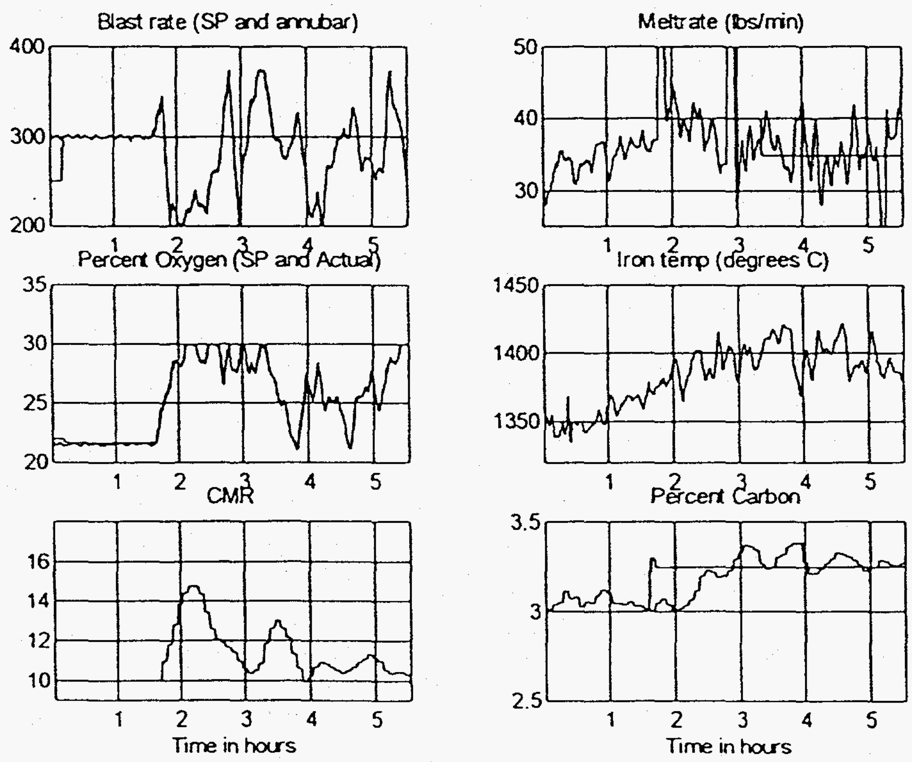

Figure 3: Simultaneous control of meltrate,
temperature and composition.