Optimal Choice of Cupola Furnace Nominal Operating Point

CONF-980386--1

Mohamed A. Abdelrahman
Electrical and Computer Engineering Department
Tennessee Technological University, Cookeville, TN 38505-5004
abdelrahman@ntech.edu

Kevin L. Moore
Measurement and Control Eng. Research Center
College of Engineering Idaho State University, Pocatello, ID 83209-8060
moorek@isu.edu

Abstract

One of the main goals in the operation of a cupola furnace is to keep the molten iron properties within prescribed bounds while maintaining the most economical operation for the cupola. In this paper we present a procedure to obtain the nominal values for the manipulated process variables. The nominal values are calculated by solving a constrained nonlinear programming optimization problem. Two different optimization problems are discussed and examples for using the procedure are presented.

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 should be accomplished while running the furnace at the most economical state. The state of the furnace is determined by the 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 [2-7]. In figure 1, we show a hierarchical structure of an integral cupola controller as perceived by the authors [2,7]. On the inner levels we see the implementation details and the control strategies which have been discussed elsewhere [7]. On the outermost level we see the intelligent planner and economic optimizer. The purpose of the controller at this level is to decide the optimal operating conditions for the cupola that the lower level controllers should try to maintain.

Figure 1: Schematic Diagram for the Cupola Controller

In this paper we present an optimization procedure that could be used to select the nominal operating points for some of the cupola process variables, namely blast temperature (BT), blast rate (BR), Oxygen enrichment (O₂) and coke to metal ratio (CMR). The suggested optimization procedure goes as follows:

- 1- Decide on an economic goal to be achieved such as maximizing profit or minimizing cost.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
electronic image products. Images are
produced from the best available original
document.**

- 2- Determine the operational constraints and requirements such as the possible and required ranges of the manipulated variables and output parameters.
- 3- Determine a mathematical input-output relation.
- 4- Formulate and solve, if possible, a constrained nonlinear optimization problem.

2 Economic Goals

In the operation of any industrial plant certain objectives have to be satisfied. In most of the plants that objective is increasing the profit. This is achieved partially by reducing the cost of operation of the plant. The net profit, however, depends on maximizing the profit of each unit plus increasing the number of units produced up to the limit that the market will bear. The cupola furnace is no exception. The reduction of the cost of the ton of metal produced might be advantageous, but it might not always yield the maximum profit because the minimum cost per ton can correspond to operating the furnace at a less than optimal melt rate. On the other hand, there are situations under which the cupola production is limited by the molding line speed. Thus, the melt rate is merely a constant determined by the molding speed. In this case, the optimization problem could be cast into the problem of reducing the cost per ton of the produced metal.

The objective function for the first case is

$$\text{Max } (J = MR \cdot SP - CPH) \quad (1)$$

where, SP is the selling price per ton and CPH is cost per hour of cupola operation. CPH is calculated from:

$$CPH = CPHM + CPHC + CPHO + CPHB + CPHH + OC$$

$$CPHM = MR \cdot \text{MetalCost}$$

$$CPHC = MR \cdot CMR \cdot \text{CokeCost}$$

$$CPHO = O_2 \cdot (BR + O_2 \cdot BR) \cdot \text{OxygenCost}$$

$$CPHB = BR \cdot \text{BlastAirCost}$$

$$CPHT = BR \cdot \text{BlastAirHeatingCost} \quad (2)$$

where, CPHM, CPHC, CPHO, CPHB, CPHH are the cost per hour for metal, coke, oxygen, blast, and blast heating and OC is a constant that represents other operational costs that we do not consider in details here. For the second case, the MR is constant and hence the optimization goal is:

$$\text{Min } (J = CPT) \quad (3)$$

where CPT is the cost per ton = CPH/MR.

3 Operational Constraints

These constraints are imposed by physical limitations and desired properties of the molten iron. The physical limitations on the considered manipulated process variables could be written as:

$$\begin{aligned} BR_{\min} &\leq BR \leq BR_{\max} \\ BT_{\min} &\leq BT \leq BT_{\max} \\ CMR_{\min} &\leq CMR \leq CMR_{\max} \\ 0 &\leq O_2 \leq O_{2\max} \\ O_{2\max} &= \frac{0.2BR + O_{2\max_flow_rate}}{BR + O_{2\max_flow_rate}} - 0.2 \end{aligned} \quad (4)$$

Similarly, the limitations on output parameters could be written as:

$$\begin{aligned} MT_{\min} &\leq MT \leq MT_{\max} \\ MR_{\min} &\leq MR \leq MR_{\max} \\ \%C_{\min} &\leq \%C \leq \%C_{\max} \\ \%Si_{\min} &\leq \%Si \leq \%Si_{\max} \\ OGT &\leq OGT_{\max} \end{aligned} \quad (5)$$

4 Input-Output Cupola Model

The cupola is a very complex system.. Accurate modeling of the process requires careful consideration of chemical and physical principles. The American Foundryman's Society (AFS) have developed the most comprehensive model available to date [3]. The model could be used to estimate the steady state output parameters of the molten iron and other cupola parameters such as off-gas temperature and composition for a given set of input conditions. The model estimates the output parameters by solving a set of nonlinear partial differential and algebraic equations which makes it slow. Thus, an ANN model was developed in conjunction with the project. This model allows fast generation of approximate input-output relations for a specific cupola.

In this paper we have focused our attention on a small subset of input-output parameters. However, the procedure could be easily used to include any other cupola parameters that are of interest. The input parameters that we consider are: BT, BR, O₂ and CMR. The output parameters that we consider are: metal temperature (MT), melt rate (MR), Carbon percentage (%C), Silicon percentage (%Si), and Off Gas Temperature (OGT). We started by running the AFS model to generate a set of

input-output pairs that cover the operational range of interest for a specific cupola [3, 5]. A regression analysis was then performed to determine the input-output relation within that region of interest. The input-output relation was determined to be as follows:

$$MT = 7.75 BR + 0.31 BT + 1122 O2 + 13.85 CMR + 1151$$

$$MR = 1.45 BR + 10.6 O2 - 0.15 CMR + 1.06$$

$$\%C = -0.036 BR + 0.73 O2 + 0.07 CMR + 2.89$$

$$\%Si = 0.02 BR + 0.32 O2 + 1.14$$

$$OGT = 20.9 BR - 0.03 BT - 226.7 O2 + 4.95 CMR + 10.53$$

(6)

5 Formulation of Optimization Problem

Melting Capacity Limits Production

The optimization problem is formulated as the maximization of the objective function (1) subject to the constraints (4) and (5). The constraints (5) are rewritten in terms of the manipulated process variables by utilizing the input-output equations (6).

Molding Line Capacity Limits Production

In this case the optimization problem is formulated as the minimization of the objective function (3) subject to the constraints (4) and (5). We will again use equations (6) to rewrite the constraints (5). Moreover, the MR constrain becomes an equality constraint with the minimum and maximum being equal to the capacity of the molding line.

6 Examples

In this section we demonstrate the application of the suggested optimization problems described above. The values used for the nominal cost of different materials and the constraint values are presented in Table 1 and Table 2, respectively.

Parameter	Value
MetalCost	(\$/Ton) 150
CokeCost	(\$/Ton) 150
OxygenCost	(\$/SCF) 5e-3
BlastCost	(\$/SCF) 1e-4

Table 1: Cost Values

Parameter	Min	Max
BR (m3/s)	1.7	2.2
BT (C)	300	550
%O2	0	3.8
%CMR	8	13
MT (C)	1400	1800

MR	2.0	
%C	3.5	3.6
%Si	1.0	1.5
OGT (C)	0	100

Table 2: Constraints Values

First, we consider the optimization problem in which the melting capacity limits production. Solution of the optimization problem was performed using Matlab optimization toolbox [8]. The optimization procedure, was repeated for the oxygen cost shown in Table 1 increased by different percentages while keeping all other costs fixed. The obtained optimal nominal values for the manipulated variables are shown in Table 3.

% increase in O2 cost	BT (degC)	BR (m ³ /s)	%O2	%CMR
0%	300	2.2	3.8	9.44
20%	300	2.2	3.8	9.44
22%	300	2.2	3.7	9.45
23%	300	2.2	3.2	9.5
24%	300	2.2	1.5	9.7
25%	300	2.2	0.05	9.84

Table 3: Optimal Parameters for Cupola Operation as a function of O2 cost increase

The optimal value for the oxygen enrichment is fixed over a large range of values, but starts decreasing rapidly as the cost increases beyond a certain limit. Next, we turn our attention to the second optimization problem in which the speed of the molding line determines the melt rate. The optimization problem is solved for different values of desired melt rate. The values of the optimal values of the manipulated variables are shown in Table 4 and shows a trade off between injecting more blast or increasing the enrichment of oxygen in the blast.

MR (Ton/hr)	BT (degC)	BR (m ³ /s)	%O ₂	CMR
2.0	300	1.75	0	10.65
2.5	300	2.0	0	9.74
3.0	300	2.2	1.86	9.65
3.25	300	2.2	3.76	9.45

Table 4: Optimal Parameters for Cupola Operation as a Function of the Desired Melt rate

Figure 2: Optimal Nominal Values of Process Variables as a Function of desired Melt Rate

7 Conclusion

A high level controller for a cupola iron furnace is responsible for determining the nominal operating points for the cupola. One of the major factors in determining that operating point is economy of operation. In this paper we presented a procedure to obtain the nominal values for the manipulated process variables of a cupola iron furnace. The nominal values were calculated by solving a constrained nonlinear programming optimization problem. Two different optimization problems were discussed and examples for using the procedure were presented.

8 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] 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.

- [3] 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.
- [4] 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.
- [5] 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.
- [6] 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.
- [7] M. A. Abdelrahman, K.L. Moore, "Robust Control of Cupola Iron Furnaces," in *Proceedings of the 1996 American Control Conference*, Albuquerque, NM, June, 1996.
- [8] The Mathworks, Inc. *Optimization Toolbox User's Guide*, 1997.