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INTELLIGENT CONTROL OF CUPOLA MELTING

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ABSTRACT

The cupola is a furnace used for melting steel scrap, cast iron scrap, and ferroalloys to produce cast iron. Its main energy source is coal coke. It is one of the oldest methods of producing cast iron, and it remains the dominate method because of its simplicity and low fuel cost. Cupolas range in size from 18 inches to 13 feet in diameter, and can produce up to 100 tons per hour of cast iron. Although cupola melting has a long history, automatic control has been elusive because the process has been poorly understood. Most foundries rely on the intuition of experienced operators to make control decisions. The purpose of this work, which has been underway for three years of an anticipated four year program, is to develop a controller for the cupola using intelligent and conventional control methods. The project is a cooperative effort between the Idaho National Engineering and Environmental Laboratory, the Department of Energy Albany Research Center, Idaho State University, and the American Foundrymen's Society.

THE CUPOLA PROCESS

The cupola furnace (1,2) is one of the oldest processes for making cast iron, and is still the dominant method. A cupola is a water-cooled vertical cylinder, as large as 13 feet in diameter and 60 feet tall (Fig. 1). The charge consists of scrap iron and steel, alloying ingredients, limestone, and coal coke for fuel. The charge is weighed and fed through doors near the top of the cupola. Air, usually heated and often enriched with oxygen, is blown in near the bottom through tuyeres extending a short distance into the interior of the cylinder. As the coke is consumed, the charge drops and melts. The hot exhaust gases rise up through the charge, preheating it and increasing the energy efficiency of the furnace. A continuous flow of iron emerges from the bottom of the furnace,

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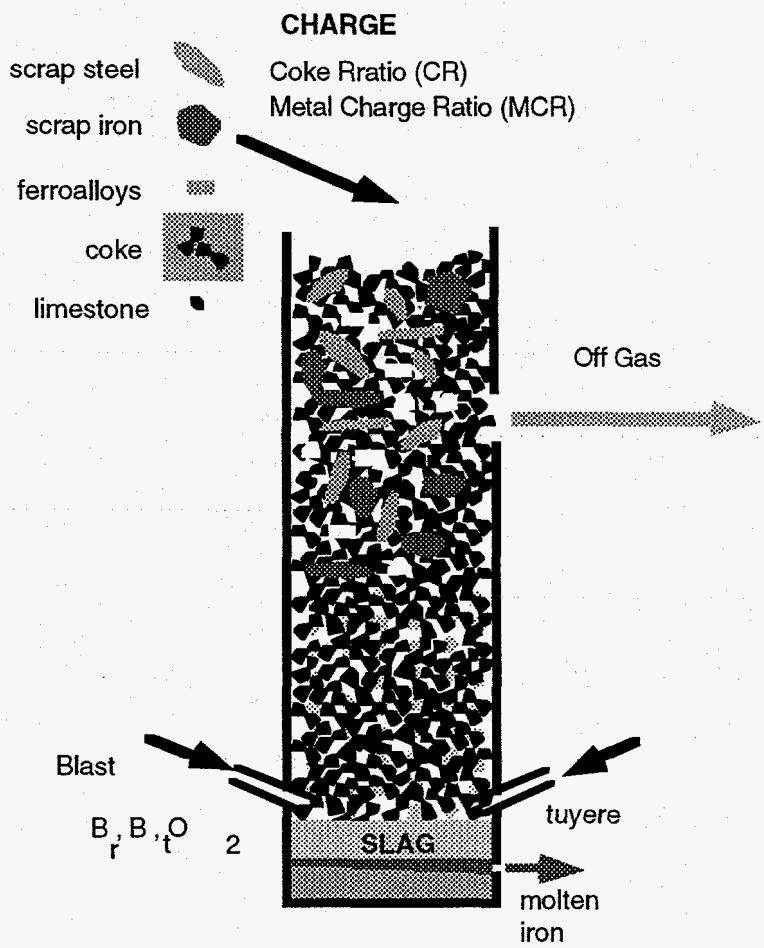

Figure 1. Cupola Schematic

at rates as high as 100 tons per hour. This molten iron is then transferred to casting lines in the foundry. The exhaust gases emerge from the top of the cupola, where they are processed to meet pollution standards. The interior environment of the cupola is very harsh. Extreme heat, chemical reactivity, large mass flows, and the presence of liquid slags and metals tend to either plug or destroy sensors that might be introduced to measure operating conditions. Partly for this reason, and partly because traditional operating methods have evolved over the centuries, the cupola is operated in open loop mode, with the expertise of experienced operators applied to obtain the desired melt rate, metal composition, and metal temperature.

Major variables for cupola control are shown in Table 1. Air blast rate is controlled by changing the speed of the mechanical blowers, blast temperature by regulating the input to the heaters, and oxygen by regulating the oxygen flow. These variables have short time constants and little delay. The metal charge ratio and the coke ratio, however, are changed by altering what is charged into the top of the cupola. It takes some time, up to an hour, for these changes to propagate with the slowly sinking charge into the active melt zone of the cupola. In current practice, these variables are not automatically controlled. While an independent control loop might be used, for example to maintain constant blast rate, it is up to the operator, based on experience, to select the blast rate and other inputs to achieve the required outputs. When the casting line needs no metal, because molds

are full, cranes are busy, or it is shut down for a shift or longer, the cupola can be "banked" with a reduced blast rate. There are transient effects associated with this event, which are more severe for longer shutdowns. A feedback control system would also be desirable during these transient phases, to reduce time and material consumption and to avoid the formation of unusable "transition iron."

The difficulty of controlling a cupola is due to the fact that the input and output variables are not independent and are cross-linked. For example, to increase the iron temperature, an operator may increase the rate of the blast air. But this would also increase the melting rate, which may be undesirable. Conventional linear control techniques are not very effective at handling control systems with significant cross-linking. Therefore, more intelligent control techniques are needed to control a cupola furnace.

Table 1: Cupola Control Variables

Output	Primary Input	Secondary Input
Iron Temperature	Blast Rate Blast Temperature Oxygen Addition	Coke Ratio
Iron composition (Carbon, Silicon, Manganese)	Metal Charge Ratio	Coke ratio Oxygen addition Blast temperature
Melting Rate	Blast rate Coke ratio	Oxygen addition

COOPERATIVE TECHNICAL APPROACH

The purpose of this work, which has been underway for approximately three years of an anticipated four year project, is to develop a controller for the cupola using intelligent and conventional control methods. The project is a cooperative effort between the Idaho National Engineering and Environmental Laboratory, the Idaho State University, the Department of Energy's Albany Research Center, and the American Foundrymen's Society.

A controller is generally developed by: (1) constructing a model of the physical system, (2) analyzing the model to determine the properties and dynamic response of the system, (3) designing a control algorithm which, when coupled with the model of the system, results in the desired closed-loop behavior, and (4) implementing the controller through either hardware or software. A finite difference model of the process provided by the American Foundrymen's Society will be used for controller development. The steady-state conditions and the dynamic response of cupolas will be determined from the model and from experimental data. An artificial neural network trained using the backpropagation algorithm will be used to learn the relationship of the steady-state process for use with the controller.

AFS NUMERICAL MODEL

The American Foundrymen's Society, an industry group with a strong interest in cupola control and optimization, has developed a numerical model of the cupola process. It is a one-dimensional, steady-state code that takes into account various chemical and geometric materials properties, chemical reactions, heat transfer, various charge materials, and various input parameters. This model has been verified with experimental data, and is expected on the market within the next year.

This software will prove very useful to cupola operators in assessing the metallurgical and economic effects of parameter changes. By correlating variables that are relatively easy to sense, such as offgas composition and temperature, with others of more immediate interest that are quite difficult to sense, such as melting rate, the model opens up new feedback control paths. The calculation time of the model is, however, probably not fast enough for real-time feedback control of the cupola.

NEURAL NETWORKS

Neural networks have recently become more popular as a way of dealing with nonlinear systems with many inputs and outputs (3). They consist of neurons (Fig. 2) and processing elements that do relatively simple calculations such as summing inputs and applying a nonlinear function to produce a single output. Many such elements, arrayed in several layers and variously connected (the "neural network"), can give fast answers to complex problems (Fig. 3). The "neural" nomenclature applied to artificial neural networks (ANNs) is a deliberate reference to the way biological nervous systems are perceived to function. ANNs are typically implemented in software. Like biological nervous systems, artificial neural networks must be trained to solve particular problems. Initial work with ANNs in the 1960s was limited because of the lack of learning techniques, but the development of the backpropagation algorithm provided a simple, iterative way to train networks. This algorithm can take many iterations, often requiring hours of computer time, using a training set consisting of known inputs and outputs, to set the weights multiplying the input to each neuron. Once the network is trained, however, it operates in the feedforward mode, which a computer can solve very quickly.

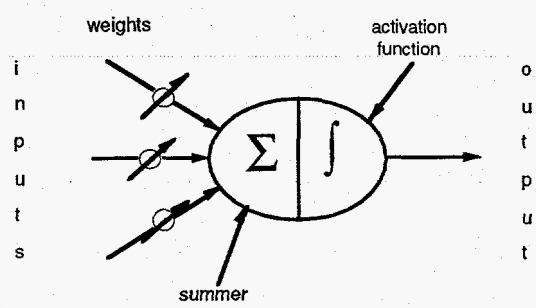

Figure 2. Nonlinear Neuron

NEURAL NETWORK IMPLEMENTATION OF THE AFS NUMERICAL MODEL

A neural network has been trained to approximate the output of the AFS model. The training set for the neural network was made by making a number of model runs, varying the inputs over a range of typical operating parameters. The trained network approximates the AFS model quite accurately. As long as the model is operating within the range of inputs covered by the training set, it can be expected that the network will allow accurate interpolation. Since the neural network is only an interpolation of a data set, however, and not a valid physical model, it cannot extrapolate outside of the original training limits. Nonetheless, because large data sets can be created easily, and networks trained from them in an automated fashion, fairly complete coverage of the operating space of the cupola can be obtained. Because the neural network operating in the feedforward mode is very fast,

with only a few hundred addition and multiplication operations required, the calculation of outputs from a given set of inputs seems instantaneous to the user, and even a quite modest personal computer can provide a response fast enough for control purposes.

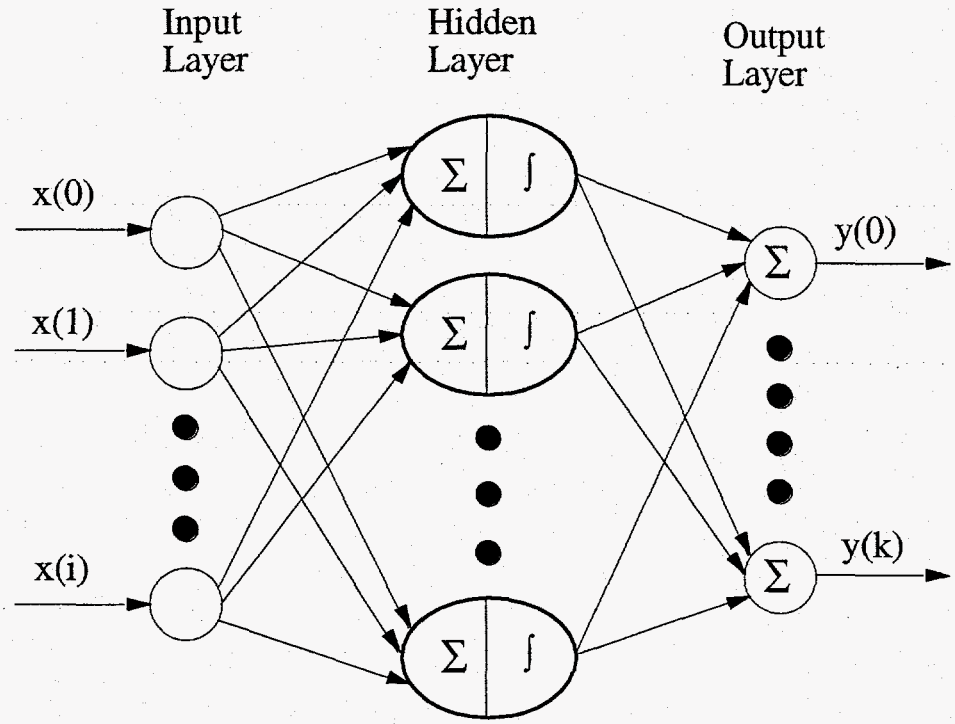

Figure 3. Feedforward Artificial Neural Network

CONTROL ALGORITHM

The planned control algorithm is a two-level, hierarchical control architecture (Fig. 4). The two levels of the control system are the system level controller and the process level controller [4]. The system level controller takes input from the process operator about iron requirements such as iron temperature and composition. The system level controller then acts to optimize economics by determining the set points that will produce the most efficient melting process. This is primarily a feedforward controller that uses information about the raw materials available in the foundry and knowledge about the operation of the cupola. The system level controller makes use of fuzzy logic algorithms to take advantage of operator expertise. After the system level controller has made determination about optimal set points, these set points are given to the process level controller. The process level controller is a feedback controller that uses measurements of process outputs to adjust the inputs so the outputs follow the desired set points. The control at this level uses a multivariable feedback controller with predictive techniques to deal with time delays in the furnace. The process level controller provides set point tracking and disturbance rejection, along with improved transient response. Both the process level and system level controller use neural networks that continue to learn during cupola operation. This continuous learning will allow the controller to respond to changes in the cupola operating conditions over time.

EXPERIMENTAL CUPOLA

An experimental-sized cupola has been constructed at the Department of Energy's (formerly Bureau of Mines) Albany Research Center in Albany, OR. The cupola has an outside diameter of 30 inches and a nominal operating diameter of 18 inches [5]. It is a front slagging type of cupola with a "T" spout design. The furnace has four water-cooled tuyeres that feed the blast air into the cupola. The overall height of the cupola is 194 inches. The cupola produces approximately 2000 lbs. of cast iron per hour, which is considerably less than a typical industrial cupola. The low production rates makes this cupola very economical to operate for experimental purposes.

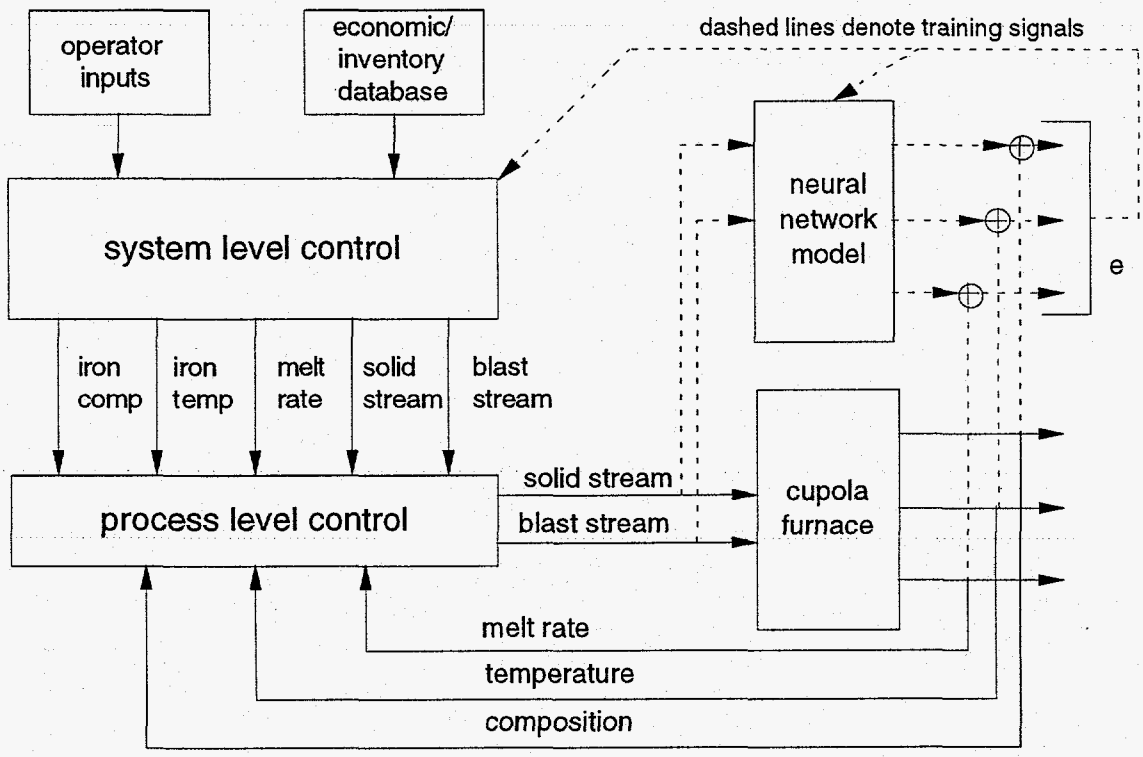

Figure 4. Control Schematic

The cupola and the air pollution system are fully instrumented to gather experimental data. Data from the cupola include pressure and temperature profiles in the blast stream, cupola interior, and exhaust gas. The temperature and flow rate of the cooling water are measured so that energy balances can be calculated. The exhaust gas is analyzed in real time for CO, CO_2, H_2, O_2, N_2, and water vapor.

MELT TESTS

To date, six metal heats have been completed at the Albany cupola, producing from 2 to 4 tons of cast iron per test. Data have been gathered on all on the heats and are being used for verifying the AFS numerical model. A charge material commensurate with industry practices has been used and the product consistency monitored. The typical feed material consists of a metallic charge of

approximately 32% scrap cast iron, 34% pig iron, and 16% shredded auto scrap. Several alloying materials such as ferro-silicate have also been added to the charge. Coke was added to the charge to obtain a metal-to-coke ratio of 13.5% coke by weight. The target cast iron composition has been 3.2-3.5% carbon, 2.1-2.4% silicon, 0.5-0.7% manganese, and <0.15% sulfur. Process variables such as stack gas composition and temperature, melt rate, and product composition were monitored during the runs and the data recorded.

All of the cupola tests to date have been to verify steady-state operation of the cupola. For control purposes, both steady-state operational parameters and the transient response of a system are needed. A series of tests is scheduled to determine transient response of the cupola. The tests are to be completed by mid-summer 1997. The data gathered from the tests will be used to finalize the design of the cupola control algorithm.

FUTURE MODIFICATIONS

Several modifications are planned for the cupola. These modifications include a new gas-fired blast system and exhaust duct, a video camera to monitor the interior of the cupola, and secondary gas analysis for CO and CO_2. The bulk of the modifications will be complete in late summer of 1997. The modifications will not only improve the experiments needed for the control system, but will also make the cupola a more attractive test bed for other cupola-related experiments.

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REFERENCES

1. American Foundrymen's Society, Cupola Handbook, 5th ed., American Foundrymen's Society, Des Plaines, IL, 1984.
2. American Society for Metals, Metals Handbook: Melting and Casting of Ferrous Metals, 8th edition, vol. 5, 1970.
3. G. E. Hinton, "How Neural Networks Learn from Experience", Scientific American, September 1992, pp. 145-151.
4. K. L. Moore, "AFS Oversight Committee Meeting - Intelligent Cupola Control Project", June 1995.
5. P. E. King, "Intelligent Control of the Cupola Furnace", Status Report to the American Foundrymen's Society Cupola Research Technical Oversight Committee, June 1996.