# Fuzzy Temperature Control for Melting Metals of Mini Cupola Furnaces

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***Abstract***

This paper presents the design of a fuzzy control system to manage the temperature of mini cupola furnaces. The melt of metals process described in chemical reactions occurring in cupola, was used to model and convert to a subsystem in Simulink. One of the main goals in the operation of a cupola furnace is to keep the molten iron properties within prescribed bound while maintaining the most economical operation for the cupola. Fuzzy temperature control presents a procedure to obtain the pressure values for the manipulated process variables. This is used to get optimum condition of temperature melt of metals.

***Keywords***

*Fuzzy Logic; Mini Cupola Furnace; Temperature Control; Melt of Metals*

## Introduction

Iron casting approximately 400 cupolas in the United States, account for 70% of cast iron production [10]. With an industry estimate of 60% yield on castings, this equates the direct production 1.204 million tons of carbon generating 4.412 million tons of carbon dioxide per year. And amounts to 1-2% of the total annual national production of greenhouse gas [Abdelrahman et al, 2000]. The cupola has maintained its competitiveness for several reasons. Compared with competing technologies such as arc or induction melting, the cupola uses the energy in coal more efficiently because it does not have to go through the intermediate step to produce electricity, and the required coke consumes little energy. The combustion products in cupola melting, holds another advantage over arc melting. The cupola is a relatively simple device that can be made in many sizes to suit the molten metal needs of foundries with different sizes.

While cupola melting is simple in principle—burning coke with an air blast and melting metal—the actual physical and chemical details of the process are quite complex and the phenomena occurring in the melt zone are difficult to measure directly because of the aggressive chemical environment that exists inside the cupola. Controlling these phenomena is desirable, however, to efficiently utilize energy, produce acceptable quality iron, and reduce the environmental impact of the melting process.

The inevitable random variations in charge composition, blast effectiveness, and even local meteorological conditions, however, lead to a degree of variability in the cupola output. This variability can be reduced by means of expert operation of the cupola. Reducing this variability is more important for some cast products than things; where iron temperature and composition are crucial, as in the production of automotive parts, holding furnaces, sometimes, hundreds of tons in size, are used to pool the output of one or more cupolas, and temperature and composition can be adjusted before the hot metal goes to the casting line [Frolik et al, 2000].

Iron that fails to meet specifications can cause substandard castings or even casting failure; and the material may be re-melted, but the energy spent in melting at the first time is wasted. The cost of installing, maintaining, and operating larges holding furnaces to level out the variability is an addition of producing iron. Materials such as coke breeze (fines from the handling of coke) that would cause poor operation if charged from above can also be injected through the tuyeres for added energy; the incinerator-like nature of the cupola incorporates that, and even other hazardous wastes unrelated to cupola operation, into the relatively benign cupola outputs: cast iron, CO, $CO_2$, and slag.

## Cupola Furnaces

The cupola, a furnace used for melting steel scrap, cast iron scrap, and ferroalloys to produce cast iron, is one of the oldest methods to produce cast iron, and remains the dominate role because of its simplicity and low fuel cost [King, 1996]. The cupola with the size of 27 inch shell diameter, 4.5 inch thickness of lower lining, 18 inch diameter inside lining, 80 inch tall, can produce up to 1 tons cast iron per hour, which can be called mini cupola furnaces (Fig. 1).

FIG.1 MINI CUPOLA FURNACES

A cupola heat includes not only the actual melting but all the operation which precedes and flows the period during which iron is melted [Abdelrahman and Moore, 1996]. A certain cycle of events occurs each time when a heat is made, including the following : (1) preparation of the refractory lining, bottom, and tap hole and slag hole, (2) lighting and burning in the coke bed, (3) charging, (4) melting, (5) tapping and slagging, and (6) dropping in the bottom.

## Melting Process

This paper discussed melting only, for research on at which temperature it can be controlled. Melting can be started if cupola is fully charged. Often a soaking period of 20 min to 1 hour is used to permit the stack contents to be preheated. Then the blower can be started. After blowing for few minutes, the cake becomes heated enough to cause melting of the metal charge. Droplets of iron may be seen falling past the tuyere peepholes. After 8 to 10 min from wind-on, melting progress is sufficient so that a trickle of iron appears at the tap holes if it is open. The heat is usually started with the tap hole closed so that the first iron will not freeze in it. Since the first tap is often cold, it may be pigged rather than being poured into mods. The time for first iron at the tap hole is an important measure of the correctness of the coke bed height. A time less than 8 min from wind suggests too low a bed and longer than 10-12 min suggests too high a bed for the air pressure and rate employed. Importance of the proper bed height is associated with temperature of molten iron. It is usually desired to have the iron issue from the tap hole consistently at 1510℃ to 1594℃. A low or high coke bed is one reason for iron colder than this temperature range. As blowing continues, melting progress, the cupola stack contents settle, and new charges must be added through the door as long as the heat continues. Metal and slag accumulate in the well, and may be handled by a sequence of tapping and slagging operations.

Chemical reactions can be considered to occur in three regions: (1) above the zone of melting (zone 1), (2) in the zone of melting (zone 2) and (3) below the zone of melting (zone 3). The zones are not distinct as the reactions take place over finite distances determined by the existing physical and chemical conditions.

Reactions occurring in zone 1 are calcination of limestone, oxidation of scrap and sulfidation of scrap, which reactions endothermic. Limestone decomposes in the cupola shaft to form lime is:

$$CaCO_3 = CaO + CO_2 \quad (1)$$

Iron scrap is partially oxidized to FeO that is assumed to create a porous oxide film through which iron diffuses to react with $CO_2$ at the gas/oxide interface. This reaction takes place a short distance above the melt zone. Chemical reaction is:

$$Fe + CO_2 = FeO + CO \quad (2)$$

React sulfide dioxide with iron to form iron sulfide (sulfidation) and iron oxide, produced in this zone. The overall reaction is:

$$SO_2 + 3Fe = FeS + 2FeO \quad (3)$$

The modeling mechanism based on reaction kinetics assumes that iron diffuses through the oxide top layer the gas/solid interface where reaction eq.3 takes place. The amount of $SO_2$ reacting according to reaction eq.3 is proportional to the surface to volume ratio of the scrap. Any unreacted $SO_2$ exits in the cupola with the exhausting gasses.

Reaction occurring in the zone 2, the primary reaction, is melting of scrap and alloys which are endothermic processes:

$$Fe_{solid} = Fe_{liquid} \quad (4)$$

This reaction taking places, which depends on the melting point of the scrap or alloys and its thickness, is:

$$FeSi_{solid} = FeSi_{liqud} \quad (5)$$

The zone 2 has exothermic process which is:

$$FeSi_{liquid} = FeSi_{steel} \quad (6)$$

Melting of ferrosilicon is followed by dissolution in the liquefied scrap. The heat related increased with the silicon content of the alloy.

Oxidation process occurring alloys by FeO begin in this zone. The available FeO is the amount introduced as rust on the charge material and that is produced above the melt zone. Reaction endothermic is:

$FeO + C_{iron} = CO + Fe$ (7)

Reaction exothermic is:

$FeO + ½ Si_{iron} = ½ SiO_2 + Fe$ (8)

The model considers the following sequence of reactions:

$SiC_{solid} + FeO_{liquid} = Si + Fe + CO$ (9)

If the FeO is exhausted by this reaction the remaining carbon dissolves in iron. If FeO consumes all the carbon and FeO is not exhausted then silicon reacts with FeO by reaction eq.8. If all the silicon is consumed and some FeO remains, it enters the slag layer where further reactions occur. The free carbon in the briquette is added to the fuel and silica and cement are added to slag.

Once iron and steel is melt, it dissolves carbon from the coke. The dissolution process continues to the top of the slag layer. The reaction is endothermic:

$C_{coke} = C_{iron}$ (10)

The dissolution rate is different for iron or steel as it is determined by reaction kinetics which is governed by sulfur concentration, temperature and carbon equivalent to the liquid metal, the size of metal drops, the ash content and size of coke and the velocity of the falling drop. The size of iron drops is determined experimentally as it is much smaller than that obtained from theoretical predictions.

Reaction occurring in the zone 3, is composed of four regions, (1) immediately below the melt zone is the region where air is introduced through water-cooled pipes called tuyeres extended into the cupola (see Fig.2), (2) below this region is one composed of coke through which iron and slag drops fall. There is no gad flow in this region or below, (3) the next zone is a layer of slag, usually less than two feet thick, and (4) the bottom layer is a layer of iron which passes out of the cupola trough the tap hole.

## Control System Design

A conventional single loop control system adjusts controlled output temperature only by the feedback signal from a temperature sensor. Pressure changes in the melt are regarded as noises to this system. Designing a conventional controller for this kind of system is difficult and time consuming. However, using a fuzzy controller, we can deal with this problem simply by taking factors (such as *pressure*) which have influence on the output, into account when designing the controller. To create a fuzzy controller for the above system, what we need to do is to establish rules that contain not only *temperature* but also *pressure* in their antecedents. This design process is much easier compared with that of conventional controllers because the rules can be set using common sense knowledge and know-how from experts. Rules are English like sentences and intuitive. No mathematical model of the process is needed as in the case of conventional control. Because base temperature is critical in the process of film generation, temperature control becomes very important.

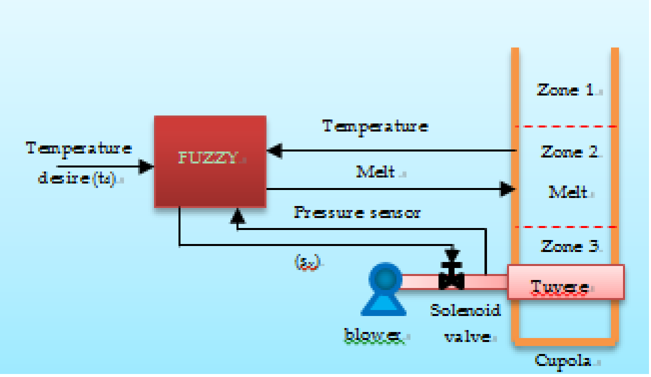



FIG. 2 DIAGRAM OF MELT TEMPERATURE CONTROL SYSTEM

Fig. 2 shows the system diagram of fuzzy temperature controller used in this kind of melting metals. Inputs to the controller are desired base temperature ($t_d$), measured base temperature ($t_m$), measured pressure in the cupola ($p_s$). Pressure is used because it has high temperature. Output signals of the controller adjust the melt ($m_t$) and the solenoide valve ($s_v$) for the air flow in the tuyeres of the cupola.

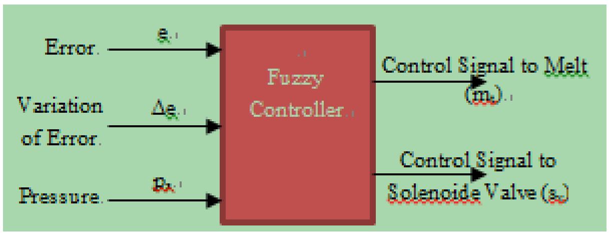



FIG. 3 FUZZY TEMPERATURE CONTROLLER

Fig. 3 shows the fuzzy controller that has three input variables and two output variables. Inputs can be prepared from feedback signals from sensors. The first input variable e is the difference between desired temperature ($t_d$) and measured temperature ($t_m$), i.e.

$e = t_d - t_m$; the second input $\Delta e$ is the variation between current temperature difference ($e_i$) and previous temperature difference ($e_b$), i.e. $\Delta e = e_i - e_b$; the third input variable is current pressure ($p_s$). Two output variables are control signals to the melt ($m_t$) and the solenoid valve ($s_v$).

### *Definitions of Input/Output Variables*

Labels and membership functions of input variables for error and variable error are defined in Fig. 4 and that for pressure is defined in Fig. 5. Those of output variables for melt are defined in Fig. 6. For membership functions whose shapes are simple, such as triangles, they are easy to be defined in a FIS (fuzzy inference system) source code.

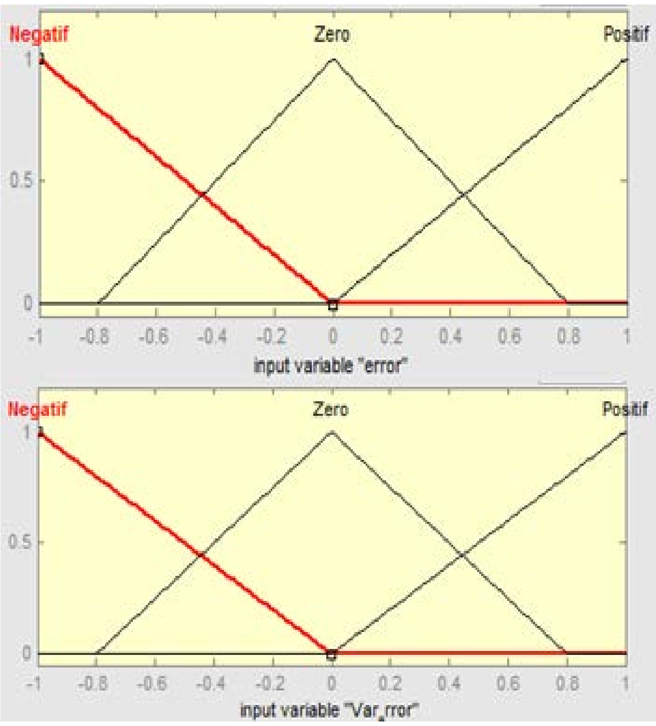



FIG. 4 LABELS AND MEMBERSHIP FUNCTIONS OF INPUT VARIABLES ERROR AND VARIATIONS OF ERROR

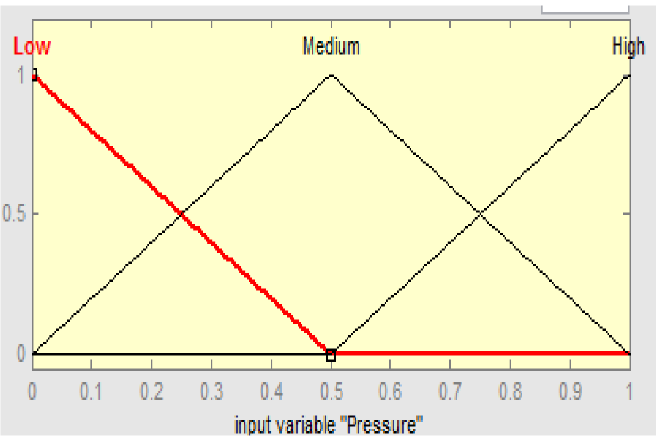



FIG. 5 LABELS AND MEMBERSHIP FUNCTIONS OF INPUT VARIABLES PRESSURE

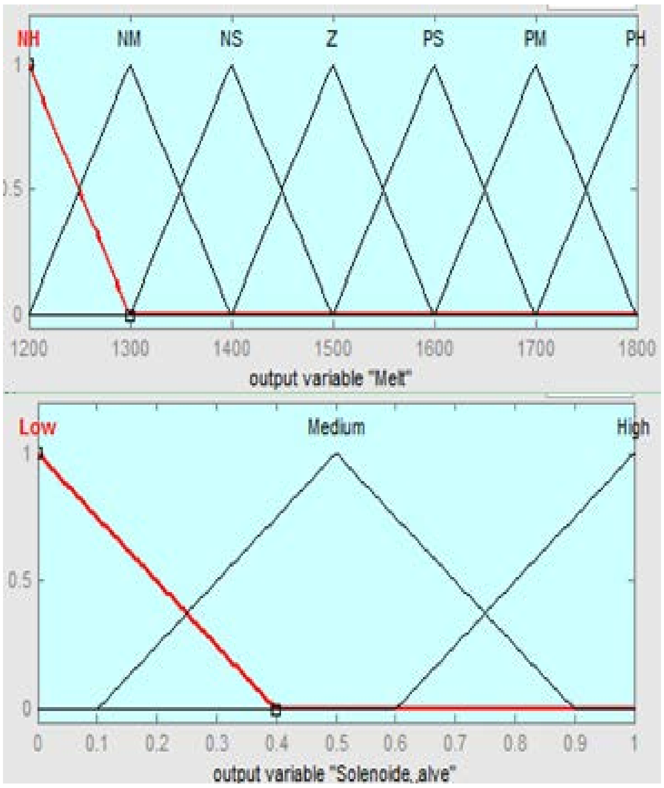



FIG. 6 LABELS AND MEMBERSHIP FUNCTIONS OF OUTPUT VARIABLES MELT AND SOLENOIDE VALVE

### *Fuzzy Rules*

The guiding principle to establish rules of this automatic focusing system is that the likelihood of an object at high distance is higher than 1500℃, medium distance is 1500℃, and at low distance is lower than 1500℃. Fuzzy rules can be seen in Table 1.

TABLE 1 FUZZY RULES

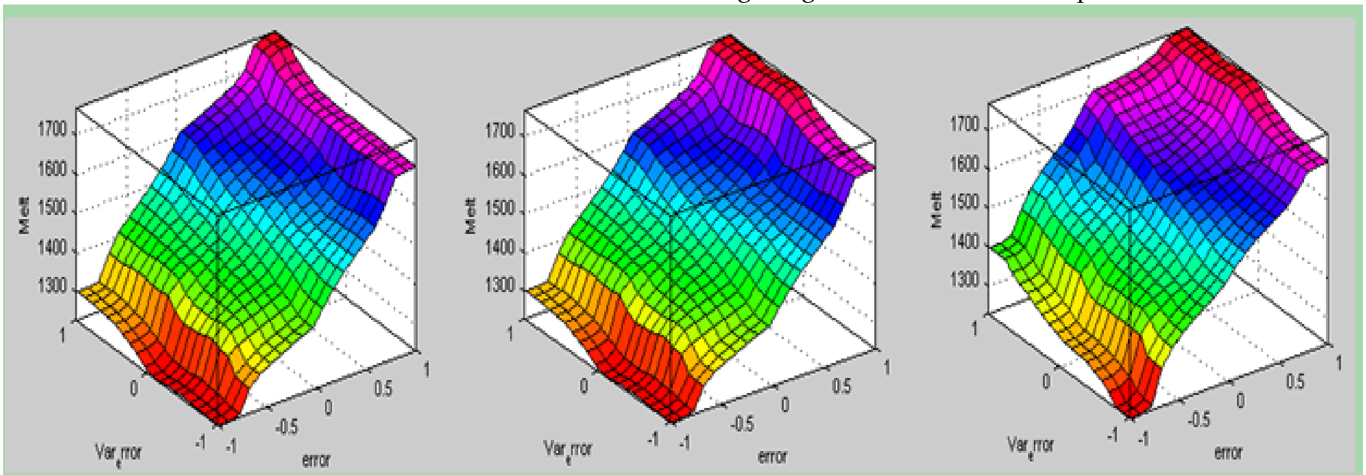
| No | Input | | | Output | | No | Input | | | Output | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | e | Δe | $p_s$ | $m_t$ | $s_v$ | | e | Δe | $p_s$ | $m_t$ | $s_v$ |
| 1 | N | N | L | NH | H | 15 | Z | Z | H | PS | M |
| 2 | N | N | M | NH | H | 16 | Z | P | L | PS | M |
| 3 | N | N | H | NH | H | 17 | Z | P | M | PS | M |
| 4 | N | Z | L | NH | H | 18 | Z | P | H | PM | L |
| 5 | N | Z | M | NH | H | 19 | P | N | L | PM | L |
| 6 | N | Z | H | NM | H | 20 | P | N | M | PM | L |
| 7 | N | P | L | NM | H | 21 | P | N | H | PM | L |
| 8 | N | P | M | NM | H | 22 | P | Z | L | PM | L |
| 9 | N | P | H | NS | M | 23 | P | Z | M | PH | L |
| 10 | Z | N | L | NS | M | 24 | P | Z | H | PH | L |
| 11 | Z | N | M | NS | M | 25 | P | P | L | PH | L |
| 12 | Z | N | H | Z | M | 26 | P | P | M | PH | L |
| 13 | Z | Z | L | Z | M | 27 | P | P | H | PH | L |
| 14 | Z | Z | M | Z | M | | | | | | |

**N = Negative; Z = Zero; P = Positive; L = Low; M = Medium; H = High; NH = Negative High; NM = Negative Medium; NS = Negative Small; PS = Positive Small; PM = Positive Medium; PH = Positive High*

### *Input/Output Response*

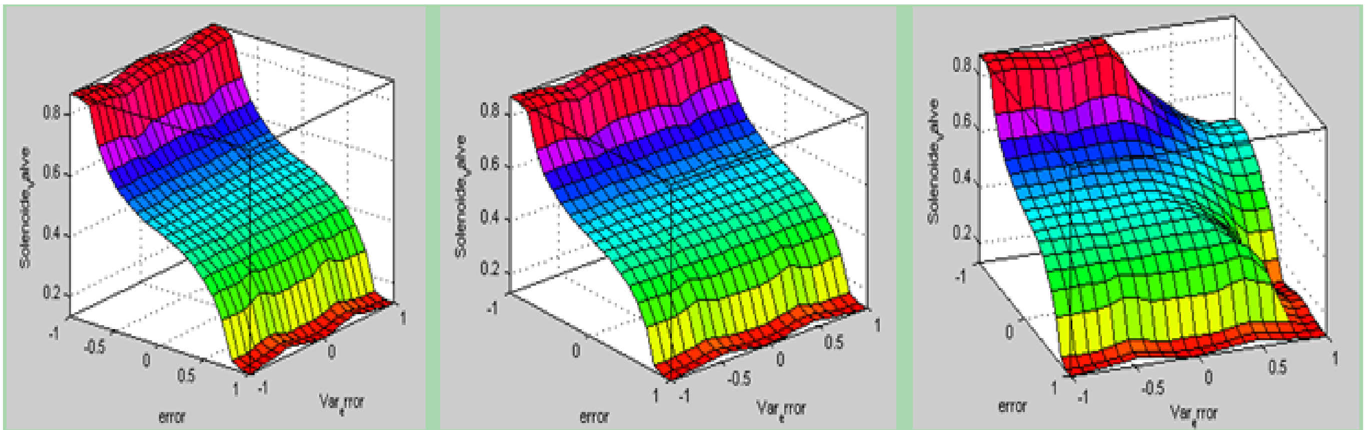
Fig. 7 shows input output response surface of the controller defined above, which are obtained by Analyzer in FIS surfview. The output in these three figures is melt, which gives the result when pressure is Low (<0.5); when pressure is Medium (=0.5) and when pressure is High (>0.5). It can be observed that the output melt becomes melted when pressure gets medium or low, when no error and when var_error is zero.

Fig. 8 shows input output response surface of solenoid valve. Similar to that in Fig. 7, the output in these three figures is signal solenoid valve, which gives the result when pressure is Low (<0.5); when pressure is Medium (=0.5) and when pressure is High (>0.5). It can be observed that the output signal solenoid valve becomes higher when pressure gets lower. This is desirable because lower pressure result in lower temperature so larger signal solenoid valve output is needed.




a) Presure is Low (<0.5) b) Presure is Medium (=0.5) c) Presure is High (>0.5)

FIG. 7 INPUT/OUTPUT RESPONSE SURFACE OF MELT




a) Presure is Low (<0.5) b) Presure is Medium (=0.5) c) Presure is High (>0.5)

FIG. 8 INPUT/OUTPUT RESPONSE SURFACE OF SIGNAL SOLENOID VALVE

## Conclusion

The proposed fuzzy temperature controller gives optimum condition for melt of metal in mini cupola furnaces. Ideal Molten iron can be acquired when no error, variation error is zero and when pressure is low or medium.

Molten iron is $FeO + C_{iron} \rightarrow CO + Fe$, whose mean is $Fe_{solid}$ and changed to $Fe_{liquid}$. The main goals in the operation of cupola furnaces are to keep the molten iron properties as specially controlled temperature. It can be obtained with the manipulated process variables as specially pressure values.

## References

Abdelrahman, M. A., Moore, K. L., "Robust Control of Cupola Iron Furnaces," in Proceedings of the 1996 Americn Control Conference, Albuquerque, NM, June, 1996.

Abdelrahman, Mohamed and Subramaniam, Senthil, "An Intelligent Signal Validation System for Cupola Furnace - Part 1 and Part 2," American Control Conference, San Diego, 1999.

Abdelrahman, Mohamed, Kandasamy, Parameshwaran and Frolik, Jeff, "A Methodology for the Fusion of Redundant

Sensors", Proc. of American Control Conference, 2000, pp. 2917-2922.

Abdelrahman, Mohamed, Moore, Kevin, Larsen, Eric, Clark, Denis and King, Paul, "Experimental Control of a Cupola Furnace," In Proceedings of American Control Conference, 1998.

American Foundrymen's Society, "Cupola Handbook", 5th ed., American Foundrymen's Society, Des Plaines, IL, 1984.

American Foundrymen's Society, "The Cupola and Its Operation", 1946, 1954.

American Society for Metals, "Metals Handbook: Melting and Casting of Ferrous Metals", 8 th ed., vol. 5, 1970.

Astrom, K.J. and Wittenmark, B., Adaptive Control, Addison-Wesley Publishing Co., Reading, MA 1989.

Friedland, Bernard, Advanced Control System Design, Prentice Hall, Inc., New Jersey, 1996.

Frolik, Jeff, PhaniShankar, C.V. and Orth, Steve, "Fuzzy Rules for Automated Sensor Self-Validation and Confidence Measure," In Proceedings of American Control Conference, June 2000.

Frolik, Jeff, Phanishankar, C.V. and Orth, Steve, "Fuzzy Rules for Automated Sensor Self-Validation and Confidence Measure", Proc. of American Control Conference, 2000, pp. 2912-2916.

Hocherman-Frommer, Judith, Kulkarni, Sanjeev R., Ramadge, Peter J., "Controller switching based on output prediction errors," IEEE Transactions on AutomaticControl, vol. 43, no. 5, pp. 596, May 1998

Hsu, Liu; de Araujo, Aldayr D.; Ramon R. Costa, "Analysis and design of I/O based variable structure adaptive control. (input-output variable structure model reference adaptive control systems)," IEEE Transactions on Automatic Control, vol. 39, no.1, pp. 4, Jan 1994.

King, P. E., "Intelligent Control of the Cupola Furnace" Status Report to the American Foundrymen's Society Cupola Research Technical Oversight Commite, June 1996.

Mulcahy, B. P., "The Cupola: Its Raw Material and Operation", Foundry, vol. 78, p 77, February-March, 1950; first of a series of articles.

Nagrath, I.J and Gopal, M., Control Systems Engineering, Second Edition, New Age International (P) Ltd., Publishers, 1995.

Yager, Ronald R. and Filev, Dimitar P., Essentials of Fuzzy Modeling and Control,John Wiley & Sons, 1994.

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