KAWASAKI STEEL TECHNICAL REPORT
No.24 (April 1991)

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1 Introduction

In recent years, considerable attention has been given to fuzzy theory,[1] which makes it possible to quantify the qualitative and approximate evaluations and judgments of human beings. Among its other uses, fuzzy control is a method of controlling manufacturing equipment by expressing the empirical knowledge of expert operators regarding control practices in the form of production rules. Suitable objects of fuzzy control include non-linear systems; systems for which it is difficult to make precise mathematical models, and systems in which dynamic characteristics vary. The number of examples of fuzzy control applied to commercial plants is increasing rapidly.[2,3] Kawasaki Steel has also applied fuzzy control to some processes.

This paper presents two examples from ironmaking processes at the company's steelworks and describes the effectiveness and future problems of fuzzy control.

2 Application to Uniform Burning Control of Sintering Machines[4]

2.1 Outline of Process and Problems

In the steelworks, the sintering process is used to pretreat iron ore as a blast-furnace raw material. An outline of the sintering process is shown in **Fig. 1**. Materials are fed from material hoppers and delivered to a mixer, then conveyed to surge hoppers and fed onto the sintering machine pallets by a drum feeder. Ignition burners ignite the surface of the material on the pallet, the coke breeze in the materials burns and generates heat, promoting the sintering reaction, and air drawn through the material bed by suction causes the sintering reaction to proceed from the upper to lower layer as the pallet moves through the sintering machine. Sintering should be completed as the material reaches the delivery end of the line. To stabilize the

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* Originally published in *Kawasaki Steel Giho*, 22(1990)3, pp. 196–202

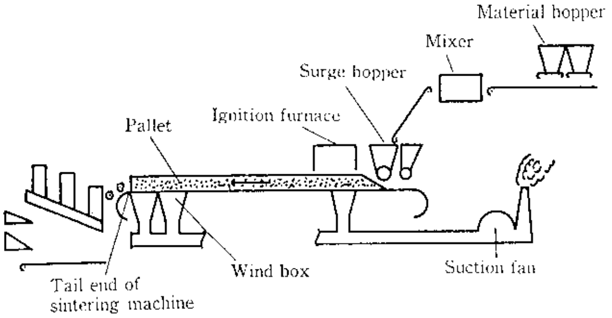


Fig. 1 Sintering process

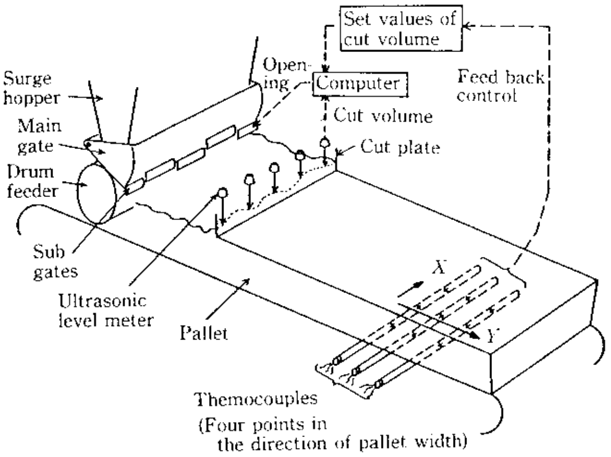


Fig. 2 Burning speed control system in the direction of pallet width

quality of sintered ore while reducing production costs, it is necessary to maintain a constant rate of burning in both the longitudinal and pallet width directions. It is desirable that in the longitudinal direction, the point at which burning is completed (burn through point: BTP) be near the delivery end of the sintering machine, and that in the pallet width direction, variations in the BTP be reduced.

Although control in the longitudinal direction is common, uniform burning control in the pallet width direction is relatively rare because of problems with the actuators and sensors necessary to effect such control and difficulties in the control method itself. In the No. 3 Sintering Plant at Mizushima Works, an attempt was made to apply fuzzy control to this problem.

An outline of the uniform burning control is shown in **Fig. 2**. To detect the BTP and determine the uniformity of burning in the pallet width direction, waste gas thermometers were installed just under the pallet in five lines in the longitudinal direction, and at four points each in the pallet width direction, for a total of 20 sensors. Variations in temperature at the four points in the width direction were adopted as an index of uniform burning. An example of current waste gas temperature variations is shown in **Fig. 3**. The distribution of the burn rate in the pallet width direction is controlled by changing the material charged density in the width direction. The charged density is expressed as the cut volume of material by the cut plate used to level the raw-material bed surface. This cut volume is measured by five ultrasonic level meters installed in front of the plate, and is controlled by five-split sub-gates for controlling the feeding rates of raw materials from the drum feeder.

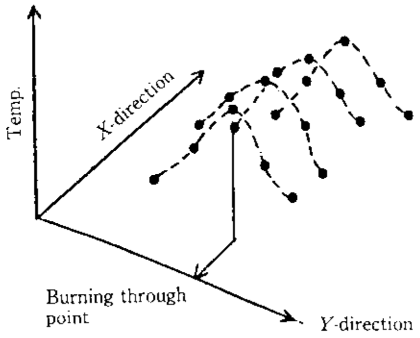


Fig. 3 Waste gas temperature distribution

2.2 Configuration of Fuzzy Control System

The uniform burning control system uses cascade control as shown in **Fig. 4**. The secondary loop of the system is the charged density (cut volume) controller in the pallet width direction with sub-gates as actuators. Sample PI control is performed by DDC. The primary loop is the center of this control system. Variations in the burn rate in the pallet width direction are detected by the above-mentioned waste gas thermometers, and set values are output to the transverse charged density control system so that variations can be reduced according to fuzzy control rules. This system, however, has a dead time of about 40 min, and is a complex system of mutual interference with multiple inputs and outputs. For these reasons, the authors considered it difficult to

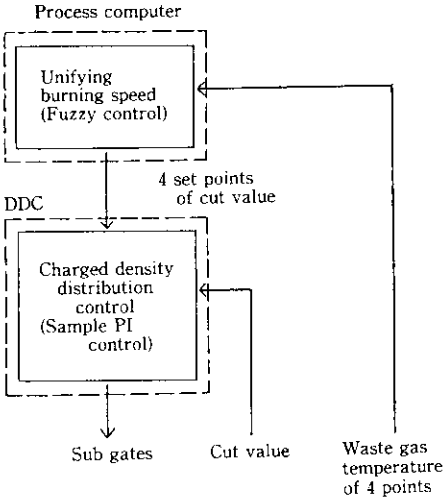


Fig. 4 Configuration of burning speed control

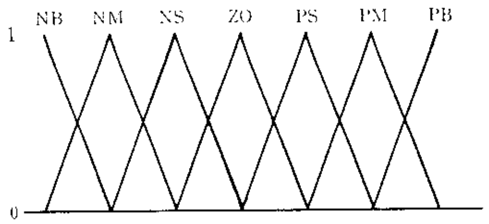


Fig. 5 Membership function

adopt a conventional control system, and applied fuzzy control based on operators' rules of thumb. The entire primary loop was implemented in a process computer.

The fuzzy set used for fuzzy control is common to the input and output sides, and is composed of the seven kinds shown below. The chevron-shaped membership function shown in **Fig. 5** was defined for each input and output item. The seven fuzzy variables have the following meanings:

NB: Negative Big
NM: Negative Medium
NS: Negative Small
ZO: Zero
OS: Positive Small
PM: Positive Medium
PB: Positive Big

The position at which the average waste gas temperature is at its maximum in the longitudinal direction is regarded as the BTP, and the deviations of the temperatures measured at the four points in the pallet width direction from the average value at the BTP position were used as input to the fuzzy control system. As outputs, there are five cut volume points. However, because the cut volume at the center of the pallet width is used as the standard and deviations are controlled on the basis of this volume, there are in effect only four output points.

The fuzzy control rules adopted are production rules. An example is shown in the following:

if [the deviation obtained by thermometer 1 is PB] then [cut volume 1 is denoted by NB] • • • • • [cut volume 4 is denoted by NS] ··················(1)

In the premise, "if"-part control is conducted at the point with the greatest temperature deviation among those measured at the four points in the pallet width direction. The number of rules is 28 in total.

2.3 Results of Control

After the verification of the feasibility of this system through a simulation, the control system was applied to the actual process, with the results shown in **Fig. 6**. Maximum and minimum values of waste gas temperature at four points in the pallet width direction were tracked in the longitudinal direction, and variations in temperature in the width direction obtained by automatic control based on fuzzy theory were compared with those obtained by manual control. With automatic control, the variations in the width direction decreased at each point in the longitudinal direction. Burn rate uniformity was improved by automatic operation. This fuzzy control system has been operating on line since May 1987.

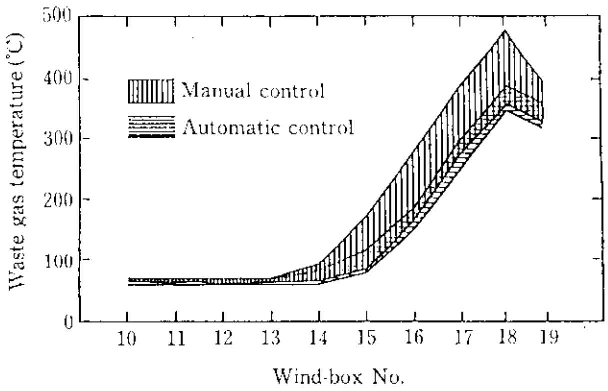


Fig. 6 Comparison of temperature differences in four measuring points between in manual and automatic controls

3 Application to Hot Stove Combustion Control5)

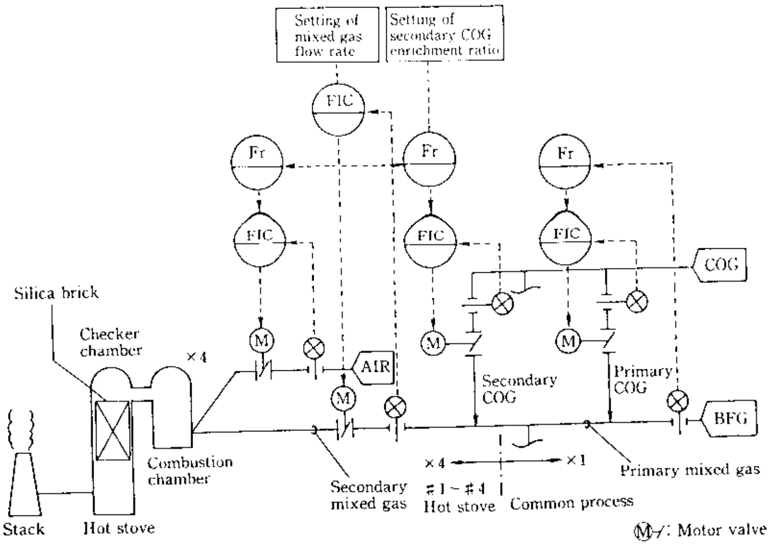
3.1 Outline of Process and Problems

A hot stove is a regenerative heat exchanger that produces the hot blast for the blast furnace. Usually, three or four hot stoves serve each blast furnace. The hot blast is produced by an alternating cycle of combustion and blast. In the combustion period, combustion gas is burned to heat the checker brick within the stove. During the blast period, a cold blast is forced through the heated checker brick, producing the hot blast which is then supplied to the blast furnace.

Figure 7 shows the flow diagram of the combustion period of the hot stoves at No. 6 BF at Chiba Works and the control system of the hot stoves. A mixed gas of BFG and COG is used as fuel. COG (secondary COG) can also be added secondarily to adjust the heat level deviations of each hot stove. **Figure 8** is a conceptual diagram of parallel blast by two hot stoves. In parallel blast by two hot stoves, the blast temperature of the blast is generally controlled by regulating the volume which passes through each hot stove using cold blast butterfly valves (CB). Silica brick is used in the principal parts of the checker chamber of the hot stove, and both the temperature at the top of the silica brick, which is called the dome temperature, and the temperature at the bottom, which is called the silica brick boundary temperature, are controlled.

Ideal hot stove operation minimizes energy costs by heating the blast to the specified temperature with the minimum quantity of gas, controlling the temperature distribution in the checker brick from the standpoint of

Fig. 7 Flow diagram of hot stove combustion process and its control system



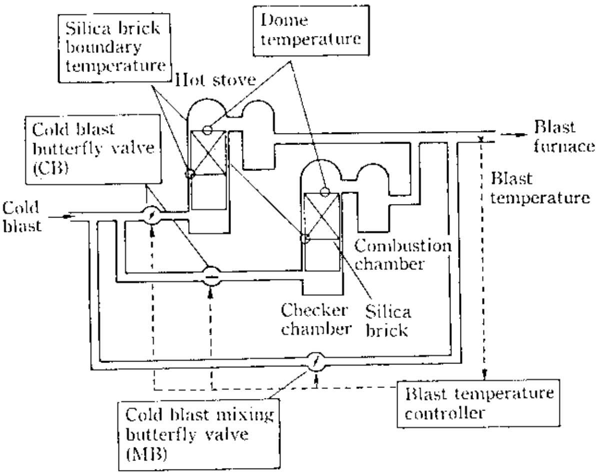


Fig. 8 Blast temperature control system in the parallel blasting operation

brick protection. The crucial problem is how to determine the optimum value of fuel gas volume during the combustion period. In Chiba No. 6 BF, where low blast temperature operation of below 900°C is used, it is necessary not only to control the minimum heat value required to maintain the blast temperature, but also to control the input heat value by setting a critical value for the minimum silica brick boundary temperature at the end of the blast period to prevent the formation of cracks due to the cubical expansion of silica brick at the transformation point (350°C or below). At the same time, it is also necessary to set a critical value for the minimum dome temperature at the end of the blast period so as to prevent gas ignition failure. In the conventional automatic setting of the combustion gas volume in hot stoves, it was considered necessary to calculate the heat balance for each hot stove based on a great deal of measured data, so determine the regenerative heat value (residual heat value) of the checker brick upon completion of blast, and to set the combustion gas volume based on the regenerative heat value thus obtained. However, no mathematical model had sufficient accuracy for both the estimation of the residual heat value by calculation and the control of brick temperature distribution. The combustion gas volume was therefore manually set each time a changeover was made from the blast period to the combustion period, but the absence of a quantitative index meant that variations in each action were great and the burden on operators was high. Giving attention to the fact that the setting of the combustion gas volume is based on multidimensional observational information and the empirical knowledge of skilled operators, the authors attempted to apply fuzzy control to the setting of the combustion gas volume.

3.2 Fuzzy Control System

At Chiba No. 6 BF, it is possible to adjust the volume of mixed gas and the ratio of the secondary COG added to it independently at each hot stove. DDC system is used in the gas flow rate control system. To give set values to the gas flow rate control system, therefore, a fuzzy control system was incorporated in a process computer.

The basic flow chart of this fuzzy control system is shown in **Fig. 9**. Set values of gas volume are output during the changeover from blast to combustion. Calculations are composed of the four steps described in detail below. Fuzzy control is applied to steps 2 and 3.

3.2.1 Step 1 Forced action for brick protection

When the silica brick temperature deviates from the target and reaches the critical lower limit value, a sufficiently large gas volume setting is fed to the stove, giving highest priority to brick protection.

3.2.2 Step 2 Judgment on process information

The operator makes judgments based on four types of information: the present stove heat level at the end

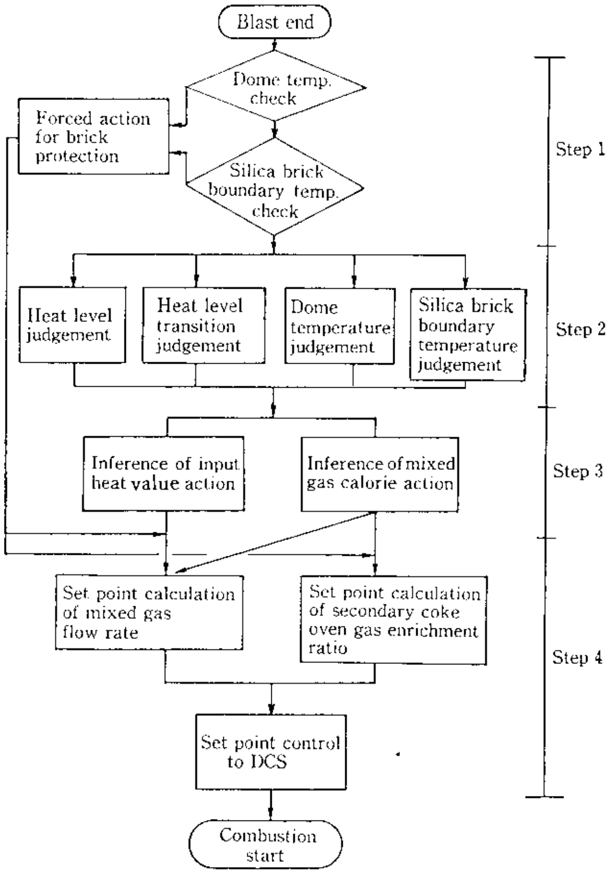


Fig. 9 General flow chart of fuzzy control model

of the blast period (residual heat value), trends in this heat level over the last several cycles, the dome temperature, and the silica brick boundary temperature. Because the stove heat level cannot be measured directly, it is estimated from the degree of opening of the blast temperature control valve (at present, MB). When the heat value is insufficient, however, the valve opening reaches its lower limit value before the end of blast period and temperature control becomes impossible. Therefore, the heat level is determined on the basis of the elapsed time from the moment the valve opening reaches its lower limit to the completion of blast feed. The heat level trend is indicated by an index of interval [−1, 1], which shows whether the heat level tends to increase or decrease based on the degree of MB opening and the brick temperature over the last three cycles.

Based on these four process information items, a three-stages fuzzy set is defined using the trapezoidal membership function shown in **Fig. 10**, by analogy with human judgments as to whether the heat level is "high," "moderate," or "low." The fuzzy variables are PB_i, ZO_i and NB_i (i = 1 to 4), following the definitions described in Sec. 2.2.

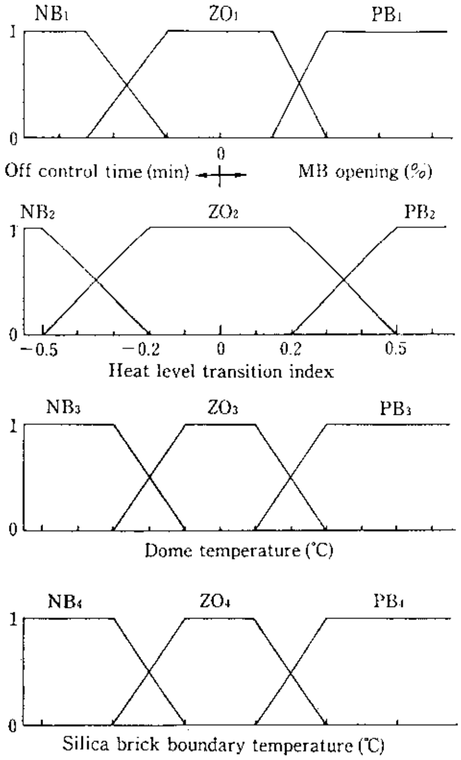


Fig. 10 Membership functions for process information judgement

3.2.3 Step 3 Inference of action values

The input heat value during the combustion period and gas calorie level per unit volume are given so as to correspond to the mixed gas volume and enrichment percent of secondary COG, which are the final outputs. **Figure 11** is a conceptual diagram of conventional manual operation.

To minimize the residual heat value at the end of the blast period, the present stove heat level and heat level transition are observed as a basis for the actions shown in Fig. 11 (a). Further, to control the brick temperature at the end of the blast period, the dome temperature

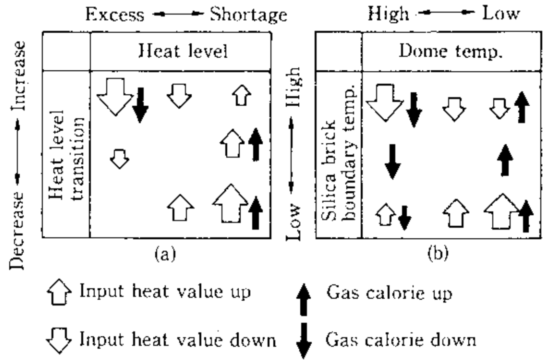


Fig. 11 Conceptual diagram of conventional operation

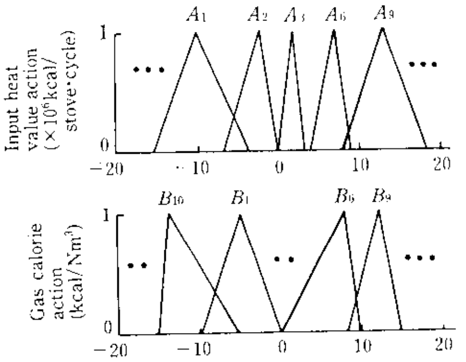


Fig. 12 Examples of membership function for action value

and silica brick boundary temperature are observed, and the actions shown in Fig. 11 (b) are taken. In terms of energy-saving, it is desirable that these two temperature variables be slightly above the critical lower limit values at the end of the blast period.

These operations by the operator are systematized based on fuzzy inference. For the action values of input heat value and gas calorie level, multiple fuzzy sets are defined using the membership functions shown in **Fig. 12**. Inferences are made according to the control rule described in fuzzy production rules in "if... then" form. Based on the operation method shown in Fig. 11 and the three-stage fuzzy set determined in Step 2, the rules can generally be expressed as follows. The number of rules is 18 for each action, totaling 36.

if $x_1 = A_{1k}$ and $x_2 = A_{2k}$ then $y = B_k \cdots$ (2)

where x_1: Heat level or dome temperature
x_2: Heat level transition or silica brick boundary temperature
A_{1k}, A_{2k}, B_k: Fuzzy variables
y: Input heat value action or gas calorie action

The number of k's is equal to the number of rules applied in determining one output.

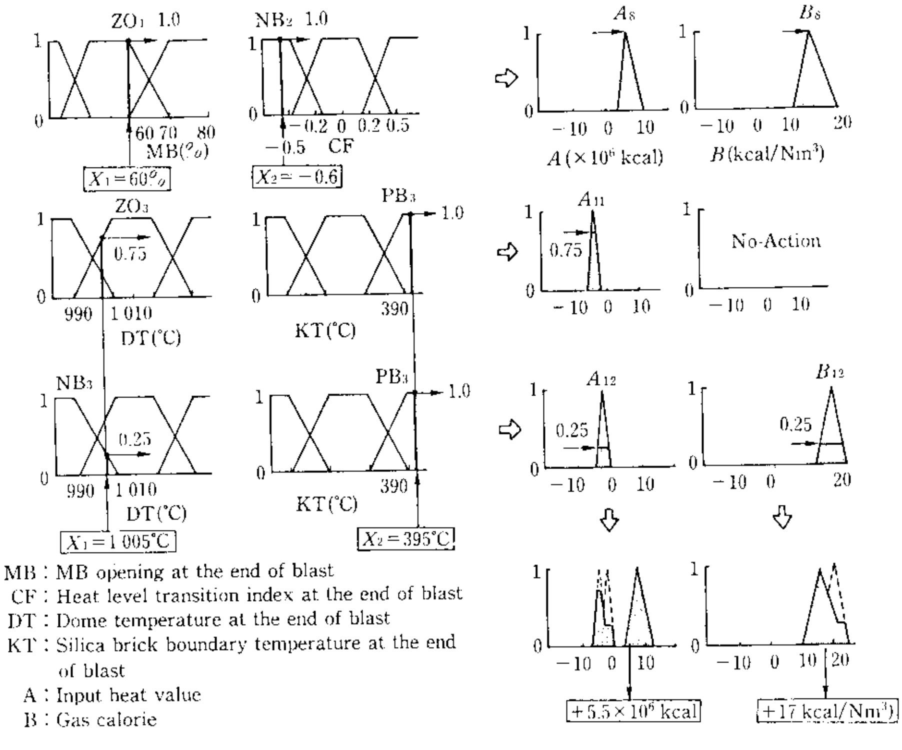
Fuzzy inference is then conducted according to a method based on the compositional rule of fuzzy relations. Supposing that the rules are OR-connected, the fuzzy set of action values is found as follows for the input heat value and gas calorie level respectively. If the membership functions corresponding to the fuzzy variables A_{1k}, A_{2k} and B_k of the equation are denoted by $h_{A_{1k}}(x_1)$, $h_{A_{2k}}(x_2)$ and $h_{B_k}(y)$, the membership function $h_B(y)$ of an action to be output is given by the following equation for measured values x_1^0 and x_2^0:

$$h_B(y) = \vee\,[[h_{A_{1k}}(x_1^0) \wedge h_{A_{2k}}(x_2^0)] \wedge h_{B_k}(y)]$$
$$= \max_k[\min(\min(h_{A_{1k}}(x_1^0), h_{A_{2k}}(x_2^0)), h_{B_k}(y))] \cdots (3)$$

Here $\wedge$ is a t-norm corresponding to AND and $\vee$ is a s-norm corresponding to OR. The output of the inference must be defuzzified. The method of taking the center of gravity is adopted, and the output y^0 is found.

$$y^0 = \frac{\int h_B(y)y\,dy}{\int h_B(y)\,dy} \cdots\cdots\cdots\cdots (4)$$

An example of fuzzy inference is given in **Fig. 13**.



MB : MB opening at the end of blast
CF : Heat level transition index at the end of blast
DT : Dome temperature at the end of blast
KT : Silica brick boundary temperature at the end of blast
A : Input heat value
B : Gas calorie

Fig. 13 Example of fuzzy inference

3.2.4 Step 4 Calculation of set values

The setting for mixed gas flow rate and the secondary COG enrichment percent are calculated from the action values of input heat value and gas calorie level. In this calculation, the features of the input heat value and detached heat value of each hot stove and the blast conditions are taken into consideration.

3.3 Results of Control

Before on-line control was introduced, an off-line simulation was conducted in order to compare the performance of the fuzzy control system with the results of judgment by operators. The results of the simulation are shown in **Fig. 14**. Actions to increase or decrease blast temperature are taken on the blast furnace side, and for this reason, the stove heat level and brick temperature also vary. Because stove heat level is sufficient in the first half of the operation, the operator does not take action affecting hot stove combustion although he raises the blast temperature and at a certain time takes rapid action to increase the input heat value by a large amount. In fuzzy control, however, actions for input heat value and gas calorie changes are smooth, producing more accurate and sophisticated control results than those obtained with manual control.

In February 1988, fully automatic operation was applied to all settings, and the appropriate functioning of the system was confirmed, demonstrating that fully automatic operation is possible except when equipment problems arise and in the non-steady states existing before and after BF blast stops.

Figure 15 shows changes in the average value and the standard deviation of the silica brick boundary temperature at the end of the blast period. Deviations decreased in three hot stoves (the fourth is under repair), and it

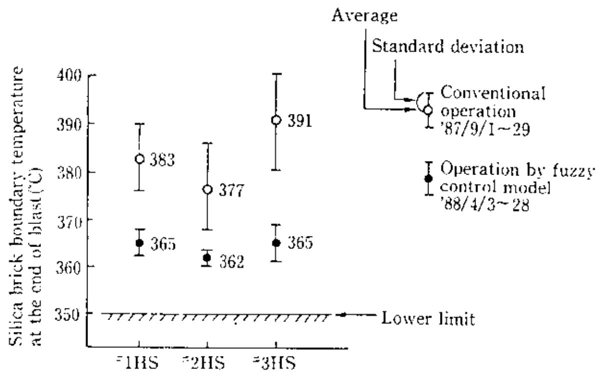


Fig. 15 Decrease of the silica brick temperature fluctuation

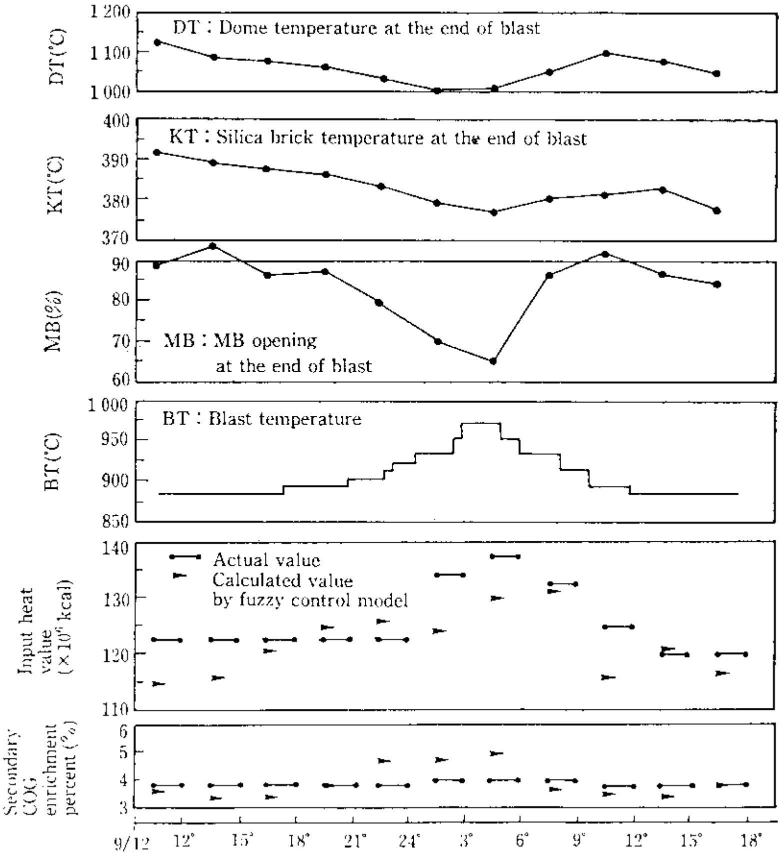


Fig. 14 Result of simulation test

was possible to lower the temperature control range to 360 to 370°C, which is very close to the lower limit. This resulted in an improvement of about 3% in thermal efficiency, which is the ratio of the actual input heat value in the hot stove to the detached heat value.

4 Features and Future Prospects of Fuzzy Control

The effectiveness of fuzzy control when it is applied to process control as described in this paper is summarized below.

(1) Fuzzy control can be applied to systems where it is difficult to apply PID control and control theory based on process models, such as non-linear systems, interfering multi-input and multi-output systems, and systems with long dead times or with time constants. Controllability is good.

(2) Because the empirical knowledge of operators can be incorporated in the system in the form of rules, the content of fuzzy control is easily understood and generally accessible to operators.

(3) If the controlled systems do not require dynamic high-speed response, they can be easily built with the use of conventional programming methods. Special hardware is not required.

However, to apply fuzzy control to wider sectors of the ironmaking and steelmaking processes in the future, it is necessary to solve the following problems:

(1) Expansion to Complex Large-Scale Process Control
In the present applications, the number of rules is relatively small and inference is conducted in one stage. From the view point of applied science, the construction of a control system for complex large-scale processes is premature, since little work has been done on the application of knowledge structuring methods and multistep fuzzy inference methods to such systems.

(2) System Tuning
Membership functions can be determined with relative ease based on the knowledge of skilled operators. However, tuning is often conducted by trial and error, and it is necessary to revise set membership functions when the operational conditions of a process change. It is therefore necessary to conduct studies on automatic tuning by neural network or other.

(3) Verification of System Stability
Thorough theoretical examinations of the stability of fuzzy control have not yet been made. Therefore, simulation experiments are an indispensable step when a control system is to be built.

(4) High-Speed Information Processing
The examples of application described in this paper posed no problems of speed. When the scope of application is expanded in the future, it will be necessary to use fuzzy computers, which are still being developed.

5 Conclusions

Uniform burning control in the pallet width direction of a sintering machine and hot-stove combustion control were discussed as examples of the application of fuzzy control to ironmaking processes. The following results were obtained:

(1) In uniform burning control in the pallet width direction of a sintering machine, fuzzy control was applied to the control of charged desity, where it is used to operate five-split sub-gates based on the information obtained by waste gas thermometers installed at four points in the width direction along five lines in the longitudinal direction. Inference is conducted based on 28 fuzzy production rules with temperature deviation as the "if"-part and cut volume at each point in the width direction as the "then"-part. Burning rate uniformity in the pallet width direction was improved.

(2) In the combustion control in hot stoves, fuzzy control was applied to the setting and calculation of the gas flow rate and calorie levels during combustion based on information on the residual stove heat value and brick temperature distribution. Fuzzy inference is conducted based on 36 rules. Automatic setting of the gas volume has resulted in an increase of about 3% in thermal efficiency.

Unlike conventional control methods, fuzzy control is easy to design and use. The authors would like to expand its application to wider fields in the ironmaking and steelmaking processes.

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