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CONTROL MODEL IN THE COMPUTER SYSTEM OF STEEL MAKING PLANT

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I. INTRODUCTION

With respect to operating techniques of steel making plant, Japan has been keeping a high reputation for her most advanced techniques. Especially, the automatic control technique by the computer system is attracting a keen attention from many countries.

To the technical background that computer control systems have been developed for a variety of processings in the steel making plant and that automatic control systems with various features have been prevailed, great efforts in the field of software technique is contributing together with a rapid hardware improvement of digital elements. In this paper we would like to introduce four typical examples of control models in the fields of software techniques.

Control models have been realized through theoretical development, and they can be classified into the following four categories according to the basic technique employed.

1 Dynamic Model : Static Model
2 Physical Model : Regressive Model
3 Deterministic Model : Probabilistic Model
4 On-Line Model : Off-Line Model

Among these models, the most suitable one is applied to each process according to its characteristics. Since all the models cited above appear in the examples of this paper, the authors wish that descriptions in this paper may best serve as a working reference for the readers.

II. OPTIMUM DISTRIBUTING SYSTEM OF TOTAL ENERGY IN THE ENERGY CENTER

1. Purpose of Control Model

Energy saving efforts in the field of steel making plants have been gaining satisfactory results. In the case of six major blast furnace companies in Japan, energy unit consumption decrease rate is 92% and oil consumption decrease rate is 71% when the consumption during 1972 is compared with that during 1978. These decrease rates are considered most excellent in the world-wide levels.

As a result, the recent trend shows a steady decrease of relatively easy problems, but a certain survey conducted in Japan predicts that a further decrease of energy of 6% is possible. As one of the methods for realizing it, such a new optimizing technique is necessary that saves existing loss of energy in the conventional operation by the cooperative operation of various kinds of processes.

In order to lessen allowances necessary for the independent operations of the conventional control and decrease managerial wastes existing in many work processes, collection of much more information and appropriate processing of the collected information are considered effective as well as improvement of measuring accuracy.

Although energy savings related to each individual facility are sufficiently advanced at present, a larger scale energy saving result can be expected as a whole steel making plant by planning much stricter optimization of plant operations. It is the Energy Center that is taking care of this specific role, and the control model used in the Energy Center is the Optimum Distributing System of Total Energy.

2. Functions of Control Model

The general concept of the Optimum Distributing System of Total Energy is illustrated in *Fig. 1*. Since improvement of the control and the energy saving of each subsystem are well progressed through continuous efforts on the part of people working in the Energy Center, it is the function of the Optimum Distributing System of Total Energy that realize much more energy saving (optimization) by the global information exchange and information processing among the different subsystems.

"Optimum distribution" of the Energy Center must be "planning smooth utilization of various kinds of energy in the whole plant, together with minimization of energy purchase cost." This idea can be expressed by the following formulation.

$$\text{minimize } f = (f_1, f_2) \quad \cdots\cdots (1)$$

$$\text{subject to } \sum_i {}^k x^i + \sum_j {}^k x^j = x^k_{\text{all}} \quad \cdots\cdots (2)$$

$$f_1 = \sum_k \sum_i \Delta^k C^i ({}^k x^i_{\text{aim}} - {}^k x^i)^2 \quad \cdots\cdots (3)$$

$$f_2 = \sum_k \sum_j \Delta^k D^j ({}^k x^j_{\text{aim}} - {}^k x^j)^2 \quad \cdots\cdots (4)$$

In the above formulas, ${}^k x^i$ and ${}^k x^j$ represent energy demands, and ${}^k x^i_{\text{aim}}$ and ${}^k x^j_{\text{aim}}$ are their aims. Also, f_1

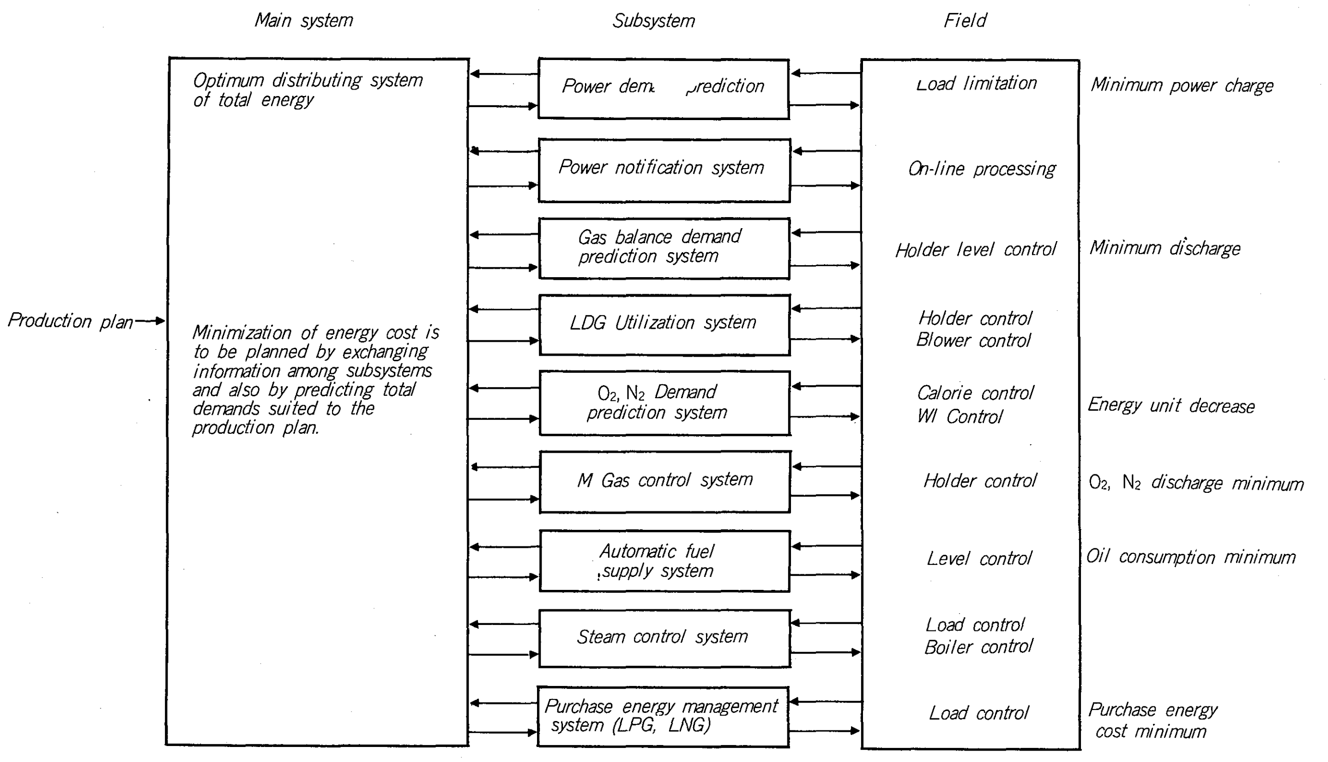

Fig. 1 Structure of a total energy optimum distributing system

represent total sum of energy cost, and such energy demand as electric power amount, purchase energy, sale energy is expressed by i, and k represents the index of energy (for example, electric power, PLG, etc.). On the other hand, f_2 represents the sum of resources that are not reflected into the cost, and corresponds to consumption of inner by-product gas in the controllable utility, and the energy demands with index j are summed up according to the energy index k.

It is the specific feature of this model that cost saving is intended through minimization of f_1, considering f_2 in such a way that the planned operating conditions may not be changed to an extreme extent, thus finding the trade-off of both f_1 and f_2.

Since coefficient $\Delta^k C^i$ corresponds to the alternative cost at the time when ${}^k x^i_{\text{aim}}$ has not been attained, it can be given with ease. However, $\Delta^k C^j$ represents the weight for the evaluation of difficulty of actual operations which is varied from the previous operation plan. Since this $\Delta^k C^j$ is not reflected into the cost even when ${}^k x^j_{\text{aim}}$ has not been attained, it is not easy to give it appropriately. Although the inner energy resources can be consumed in any way within allowable deviation range, it is necessary to obtain practical operational guidance by appropriately giving $\Delta^k D^j$ because there are certain limitations related to operations.

3. Basic Theory and Actual Method

For model analysis of the Optimum Distributing System of Total Energy, prediction theory is employed for the energy demand prediction, and optimization theory is employed for the energy demand prediction, and optimization theory is employed to get optimal energy saving plan. As prediction theory, the followings can be used.

(1) Least square method
(2) Multi-regressive model
(3) Auto-regressive model
(4) Kalman filter

For optimization theory, such techniques as shown in *Table 1* are used as convenient means, and successive calculation is adopted to realize the method.

Table 1 Optimization technique

Name of Mathematical Programming	Features
Optimization Problems without Limitation	∘ Basic theory of non-linear programming
Linear Programming	∘ Objective function, subjective; linear ∘ Continuous variable
Non-Linear Programming	∘ Objective function, Subjective; one or both are non-linear ∘ Continuous variable
Integer Linear Programming	∘ Objective function, Subjective; linear ∘ Discrete variable (0, 1, integer)
Multi-Objective Programming	∘ Objective function; plural ∘ Linear, Non-linear, Continuous, Discrete Variable

Since the model expressed in formulas (3) and (4) is linear, it becomes the main work of the application of this model to give coefficients $\Delta^k C^i$ and $\Delta^k D^j$ in such a way that they may best fit to the operational conditions.

4. Future Scope

For energy saving of steel making plants, expectation to the Energy Center will be increased more and more. To cope with such a trend, the functions of this model have been enhanced by improving the model into which actual operational conditions may be easily incorporated so that the model can satisfy multiple objectives instead of a single objective.

III. CONTROL MODEL OF BLAST FURNACE STATE

1. Purpose of Control Model

Blast furnace state is controlled to stabilize metalogical reactions in the furnace by understanding the furnace state quantitatively and by maintaining it at a constant level. However, the physical and chemical phenomena in the furnace are complicated, and the related mathematical models have not yet been established. Further, it takes long time to analyze such complicated phenomena. Therefore, in order to realize a physical model of blast furnace state control, many difficult problems must be solved.

Taking this specific point into consideration, estimation and control of blast furnace state are performed by employing identification and optimal control method through use of multi-dimensional auto-regressive model.

2. Functions of Control Model

This model is used to predict and control Si which is an index of the furnace state.

1) Prediction of Si %

By a multi-dimensional auto-regressive model, Si % of one sample ahead is predicted, using the past time series of process variables and manipulated variables. Besides Si %, such factors as melting pig temperature, furnace top gas temperature, furnace top gas composition are used as process variables. On the other hand, such factors as fuel amount, ore feed, blow air flow, blow air temperature, blow air humidity, etc. are used as manipulated variables.

2) Furnace State Control

Set values of manipulated variables are calculated by use of coefficient matrix determined by the optimal control theory so that the values of the process variables used in prediction of Si % may agree with the set values.

3. Basic Theory and Actual Method

Generally, the auto-regressive model of multi-variable process as a blast furnace can be expressed by the following equation.

$$X(k) = \sum_{m=1}^{M} \left\{ A(m)\, X(k-m) + B(m)\, U(k-m) \right\} + W(k) \quad \cdots\cdots (5)$$

where, $X(k)$: Process variable vector
$U(k)$: Manipulated variable vector
$W(k)$: Noise vector
$A(m)\,;\,B(m)$: Coefficient matrix

Through use of time series data, $\left\{X(k), U(k), k=1\sim N\right\}$ in the equation (5), constants of the model $\left\{A(m), B(m), m=1\sim M\right\}$ and M are obtained by means of Akaike's FPE method, so that the error variance should be minimized. With the auto-regressive model expressed by the equation (5) determined, it is converted into the following state equations (6) and (7).

$$Z(k+1) = \Phi Z(k) + \Gamma U(k) \quad \cdots\cdots (6)$$

$$X(k) = [I, 0 \ldots 0]\; Z(k) \quad \cdots\cdots (7)$$

where,

$$Z(k) = \begin{pmatrix} X(k) \\ X(k-1) \\ \vdots \\ X(k-M+1) \\ U(k-1) \\ \vdots \\ U(k-M+1) \end{pmatrix} \quad \cdots\cdots (8)$$

To this model, control output $U(k)$ which minimizes the following quadratic criterion

$$J_I = \sum_{i=1}^{I} \left\{ X'(i)\, QX(i) + U'(i-1)\, RU(i-1) \right\} \quad \cdots\cdots (9)$$

can be obtained by the following equation.

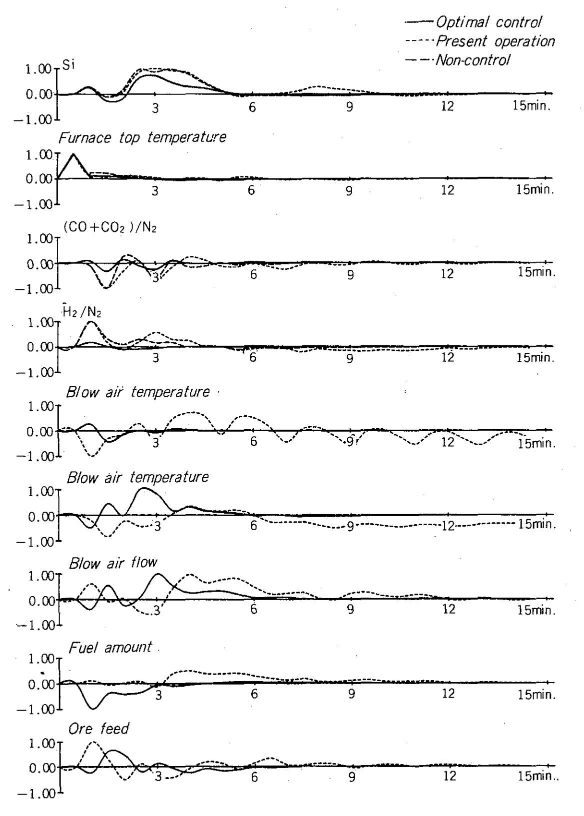

Fig. 2 Simulation results of blast-furnace state control

$$U(k) = -GZ(k) \quad \cdots\cdots\cdots\cdots \quad (10)$$

where, G is the optimal feedback gain obtained by dynamic programming.

4. Application Example

Figure 2 shows the simulation result of optimal control by this model, the control of actual operations and the result of non-control operations in the case where pulse-wise disturbance has been applied to the furnace top gas temperature. The process variables are Si %, furnace top gas temperature, $(CO\,\% + CO_2\%)/N_2\%$ and $H_2\%/N_2\%$, and the manipulated variables are blow air temperature, blow air humidity, blow air flow, fuel amount, ore feed.

5. Future Scope

The control method by the estimation (identification) described here in this Section can also be widely applicable to process control of sintering furnace, LD converter, rolling process, and to energy demand prediction, etc. as well as blast furnace state control.

IV. CONTROL MODEL FOR CONTINUOUS CASTING PLANT

1. Purpose of Control Model

Among control models for continuous casting plant, auto-casting control and water flow control of secondary cooling zone are especially important in the plant operations.

1) Auto-Casting Control Model

It is the basic purpose of the auto-casting control to maintain the molton steel level in the mould constant by controlling the molton steel flow from the tandish into the mould corresponding to the casting speed. For maintaining molton steel level in the mould at a high precision, the weight of the molton steel in the tandish is controlled. For this purpose, such a control method is required that minimizes the number of movement of the ladle nozzle so that its wear should be prevented. Also, for automation of casting, auto-start and auto-stop are realizable.

2) Secondary Cooling Water Flow Control Model

Cooling in the secondary cooling zone affects the quality of the casted piece to a great extent. Conventionally, the total cooling water flow is controlled proportionally to the casting speed based on the concept of the constant water ratio, thus water flow at each zone is determined at a specific distributing ratio. However, the uniformity of the quality of casted pieces cannot be assured, because the conventional method explained above is insufficient for controlling the ununiform cooling due to a large casting speed variation as in the case of exchanging the tandish, etc. For solving this problem, on-line state estimation is made at the solidification process, and dynamic control is realized according to the value of the state estimation obtained.

2. Functions of Control Model

1) Automatic Casting Control Model

1 Molton Steel Level Control in Mould
- • PID control with backlash correction
- • PID control with backlash correction + estimation control by casting speed

2 Tandish Weight Control
- ◦ Proportional + multi-band control

3 Auto-Start, Auto-Stop Control

2) Secondary Cooling Water Flow Control Model

1 On-Line State Estimation
- • Estimation of shell thickness and surface temperature at the mould outlet
- ◦ Estimation of solidification pattern by surface temperature
- • Estimation of solidification pattern by secondary cooling water flow

2 Secondary Cooling Water Control System
- ◦ Surface Temperature Pattern Control
- ◦ Solidification Pattern Control

These control models are implemented into actual system after the simulation by a large-scale computer.

3. Basic Theory and Actual Method

1) Automatic Casting Control Model

1 Molton Steel Level Control in Mould

The block diagram of molton steel level control in mould is shown in *Fig. 3*. The PID parameters are determined so as to minimize the following criterion developed for auto-tuning.

$$\int_0^\infty \left\{ e^{\beta t} x(t) \right\}^2 dt \quad \cdots\cdots\cdots\cdots \quad (11)$$

where, x : Control deviation, β : Constant

Further, with respect to PID control output, backlash of the tandish nozzle is corrected.

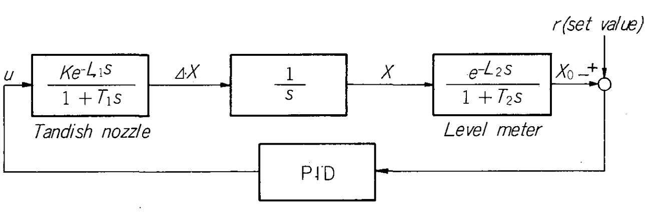

Fig. 3 Block diagram of molton steel level control in mould

2 Tandish Weight Control

Four weight levels, $W_{H2} > W_{H1} > W_0 > W_{L1} > W_{L2}$, are set corresponding to the weight set value W_0, and opening of the ladle nozzle is controlled by the following logics.

(a)	$W_k < W_{L1}$ and $W_{k-1} > W_{L1}$ $W_k < W_{L2}$ and $W_k < W_{k-1}$	To be opened by Δx from the present opening.
(b)	$W_k > W_{H1}$ and $W_{k-1} < W_{H1}$ $W_k > W_{H2}$ and $W_k > W_{k-1}$	To be closed by Δx from the present opening.

where, W_k : Tandish weight at time k.

2) Secondary Cooling Water Flow Control Model

The base of the secondary cooling water flow control model lies in the estimation and control of solidification state. The solidification stage can be expressed by the following equations.

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial t}(k \frac{\partial T}{\partial x}) \quad 0 < x < S(t) \quad \ldots\ldots\ldots \quad (12)$$

$$\kappa \frac{\partial T}{\partial x} = \rho L \frac{dS}{dt} \quad x = S(t) \quad \ldots\ldots\ldots \quad (13)$$

where, T: Temperature, S: Shell thickness,
ρ: Density, c: Specific heat,
κ: Heat conductivity, L: Latent heat

Equations (12) and (13) are to be solved, by virtually slicing the casting piece in the continuous casting into thin elements, and by memorizing the cooling history of each element (casting temperature, released heat quantity in mould, surface temperature, cooling water flow amount) from casting up to the present time. The supersosition of this calculated results of all elements is considered as the solidification state of the continuous casting piece.

In the followings, outlines of each estimation model and secondary cooling water flow control are described. For detailed calculation formulas, please refer to the Reference (6).

(1) Estimation of Mould Outlet Surface Temperature and Mould Outlet Shell Thickness

The released heat quantity in mould is calculated from the mould cooling water flow and temperature difference, and the obtained result is converted into heat flux distribution. The estimation is obtained by using this heat flux distribution as the boundary condition of the casting piece surface.

(2) Estimation of Solidification Pattern by Surface Temperature

After obtaining the mean value of surface temperature variation from initial pouring up to the present time, the estimation of solidification pattern is calculated from this value by applying the following formula derived from Neuman's solution.

$$S(t) = 2(\kappa/\rho c)\,\lambda(t)\,\sqrt{t}\;[\lambda(t) : \text{constant}] \quad \ldots\ldots \quad (14)$$

(3) Estimation of Solidification Pattern by Secondary Cooling Water Flow

From the secondary cooling water flow, heat transfer coefficient is obtained by the following equation, and the estimation is obtained by the integration with the boundary condition of this heat transfer coefficient.

$$h = \alpha(1.0 - 0.0075\,T_W) \times W^{0.55} \quad \ldots\ldots\ldots\ldots \quad (15)$$

where, h : Heat transfer coefficient, α : Constant,
T_W : Cooling water temperature,
W: Flow density

(4) Secondary Cooling Water Flow Control Method

The flow chart of the solidification pattern control is shown in *Fig. 4*. The surface temperature pattern control

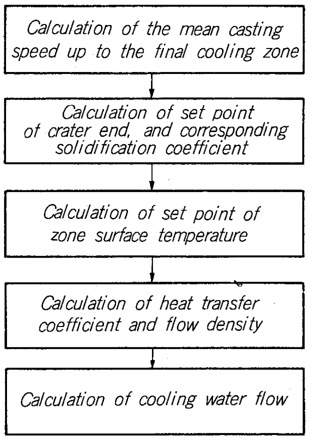

Fig. 4 Flow diagram of the second cooling water flow control

corresponds to the processings from the third block of *Fig. 4*.

4. Application Examples

1) Automatic Casting Control Model

Figure 5 shows the simulation results of tandish weight control and molton steel level control in mould in the case where auto-start by the computer system has been performed. From *Fig. 5*, we understand that the sequence control at the initial casting has smoothly changed into ordinary control and that the subsequent controls are performed satisfactorily.

2) Secondary Cooling Water Flow Control Model

In *Fig. 6* are shown the results of the actual operation by this control model and these by the conventional constant water ratio control. It is clear from *Fig. 6* that there is big difference of surface temperature behaviors between the two at the casting speed change.

5. Future Scope

In the future continuous canting plants, facility capabilities, high efficiency, quality improvement, and direct combination with rolling stage will be aimed, and thus control models with high accuracy will be needed more and more. On the other hand, the computer systems will be remarkably improved for a larger capacity and a higher processing speed and thus, control models with much more ability will be realized. Under such circumstances, development of control models with higher precision is steadily in progress through accumulating the results of on-line data analysis for the actual plants and of off-line simulation.

V. YARD CONTROL SIMULATION MODEL

1. Purpose of Control Model

There are various kinds of stock yards which are located between general steel making stages and are playing the

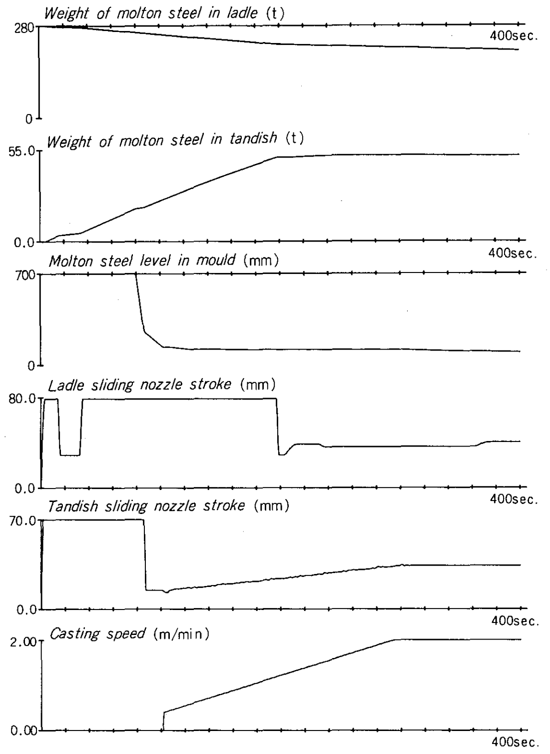

Fig. 5 Simulation results of auto start control

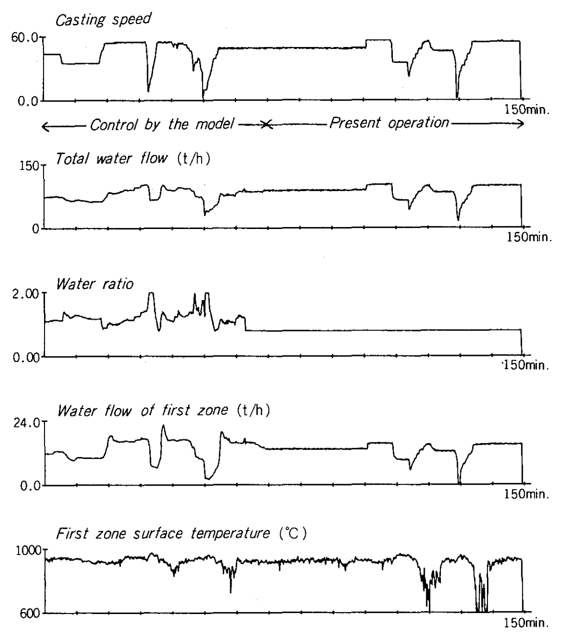

Fig. 6 Actual example of the second cooling water flow control

role as the buffer for the arrangement of the different productions.

Among such stock yards, the slab yard is located between the steel making process and the rolling process, and the coil yard is located between the rolling process and the shipment of the products. With respect to these slab yard and coil yard, simulation system available for various kinds of material handling equipment has developed, and has been used in both on-line and off-line.

It is the purpose of this simulation system to check the whole facility system by obtaining the operating status and the stock status of the transportation machines and facility equipments of all the yards. Also, when the yard is controlled by control computer system, yard operation method, especially, for scheduling or ordering, are examined in advance, and thus highly reliable software can be provided.

2. Functions of Control Model

In the following are introduced three kinds of control models.

1) Slab Yard Control Simulation

This system simulates, the operations of plural cranes which move the slab piled in the yard according to the predetermined schedules.

(1) Initialization of piling (receiving method, receiving conditions)

(2) Preparation of delivering schedule (Fix method, Float method)

(3) Crane real-time simulation
(Location selection method, location change method, ordering method, checking method of crane interference)

(4) Input: Rolling schedule, specifications of each equipment and facility
Output: Delivering schedule, rate of crane operation, final piling, time chart of cranes by XY plotter.

2) Trailer Drive Simulation Among Coil Yards

By this system, the trailer drive schedule is simulated according to the material flow from one stage to another in the yard.

(1) Preparation of scheduling for trailer operation in the sequence of cooling, cutting, skin-path, refining, product yard

(2) Ordering to the tractor and the vehicle

(3) Input: Number of coils to be moved between the yards, specifications of each equipment and facility.
Output: Rate of operations of the tractor and the vehicle, time chart for trailer and vehicle by XY plotter.

3) Coil Yard Total Simulation

This is the model of the movements of transportation machines (belt conveyor, cranes, vehicles, trailers) and facility equipment (skin-path) along with the flow of coils up to the skin-path outlet from the primary and secondary cooling yards via the skin-path preparation yard.

(1) Scheduling of the drive of transportation machines and the use of static facilities

(2) Ordering to each equipment

(3) Input: Initial yard stock, number of coils at the rolling outlet, destinations of coils, specifications of each equipment and facility.
Output: Contents of each schedule and number of coils, rate of operations of each equipment, operating status of each equipment and transient of the number of coils in each yard by XY plotter.

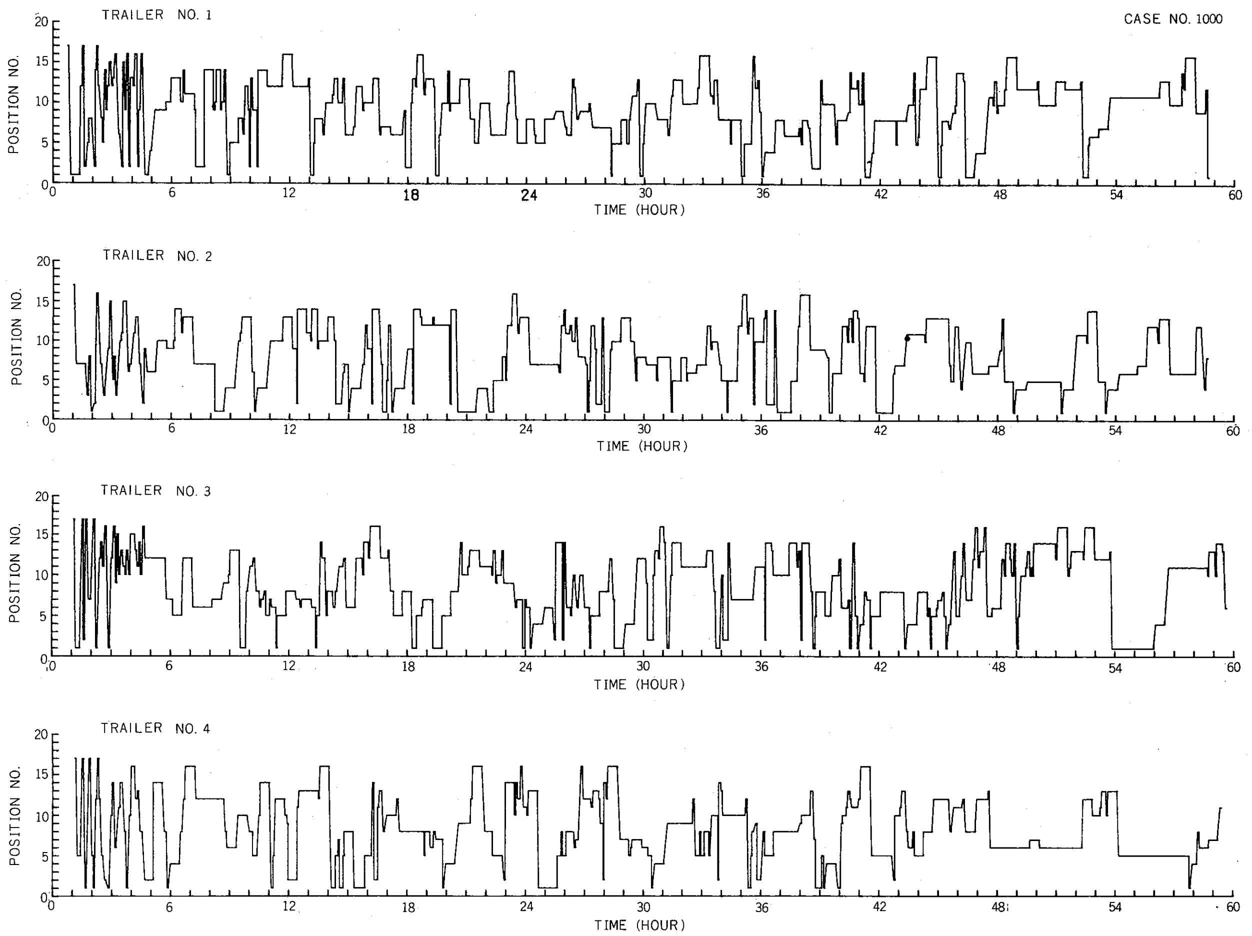

Fig. 7 Simulated movement of trailer

3. Basic Theory and Actual Method

In the case of the slab yard control simulation, discrete algorithm is employed in which the movement of cranes is represented as an activity and the time is advanced at each time when a crane movement occurs. Among scheduling orders for slab receiving into plural cranes and carrying, executable orderings are selected, and thus simulation is performed by checking the interference among the cranes. In the case of simulations related to coil yard, the operations of various equipment and movement of materials are modeled by use of random numbers, and situations difficult to obtain in actual operations can be provided as input and output through statistical technique.

4. Application Example

Movement of tractor (simulation result) obtained by the trailer drive simulation among coil yards is shown in *Fig. 7*.

5. Future Scope

The field of automatization of material handling in the steel making plant is somewhat behind the automatization of other work processes. Since this filed is greatly related to the cost, it is very important field. Especially, efficient management of yards located among various stages will very much help to promote improvement of efficiency of material flow among various work stages. Therefore, it is highly beneficial to clearly establish by simulation a method for processing the information related to the material flow and a control system of transportation machines and facility equipments.

VI. CONCLUSION

The control models described in this paper are parts of such control models that can be utilized at present.

In selection of control models, the amount and reliability of data accumulated through actual operations of various processes are most important factors. Therefore, practical control models can be realized only in the cooperations with the engineers of design, development, application, and operations of steel making plant control system. Further, utilization of a control model may sometimes go beyond the capacity of the control system makers.

Under such circumstances, we are going to continue utmost efforts to answer the users' request by making available as many packages as possible that realises the working theories and also by accumulating a variety of applicable techniques.