Model building for an ingot heating process : physical modelling approach and identification approach

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钢锭加热过程动态模型的建立
——热力学定律法及系统辨识法

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Abstract

The model building for steel ingot thermal behaviour is considered. The variables which are taken into account are the furnace temperature and the ingot central core temperature, and - sometimes - the surface temperature. The purpose of the work is to build a simple dynamical model in order to predict the central temperature. Firstly, the physical modelling is performed, making use of the heat transmission theory. Then, black-box identification is used to determine models based on the experimental data. Experimental test data are used to examine the qualities of models from both methods. The two methods are compared in several aspects.

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CONTENTS

1. INTRODUCTION

A substantial proportion of energy consumption in the process of steel rolling consists of steel ingot heating. Generally, cool steel ingots should be heated to an appropriate temperature before slabbing. The heating quality of the ingot exerts a great influence on the rolling process. Meanwhile, the heating strategy (heating temperature, heating time etc.) plays an important role in the heat efficiency of the furnace. The quality of heated steel ingot and energy consumption depends on the type of furnace, combustion efficiency and control strategy.

Experience tells us, that if the thermal states in the heating process are known, the optimal heating strategy for minimum energy

consumption can be realized by computer control. Unfortunately, there is no method for the on-line direct measurement of the steel ingot thermal states which are needed for the heating process control. Some researchers have tried to build a mathematical model which relates these variables to the variables which are needed; this model is used to estimate the steel ingot thermal state. They have used the method of lumped parameters, distributed parameters, regression analysis and state estimate [1] - [4].
But most of them are computationally complex and it is difficult to use them in practice. The contradiction between estimate precision and computational ease prevents such models from being used in practice.

For the computer control of the heavy steel ingot heating furnace at the Xining Steel Plant, we first developed a mathematical model which describes the thermal behaviour of the steel ingot heating process. The model is based on the theory of transmitting heat and new assumptions. This model has been tested at the Xining Steel Plant. Then the other the black-box identification is used to determine a model based on the experimental data of the process. Experimental testing data is used to examine the qualities of the models.

2. MODEL-BUILDING BY USING HEATING-TRANSMISSION THEORY

The aim of developing a mathematical model is to obtain a set of formulae, here, based on the physical laws of heat-transmission theory in order to describe the thermal state of the steel ingot in the total heating process, such that a computer simulation on-line control of the steel heating process can be realized.

Based on the specific furnace structure of the Xining Steel Plant, and for the sake of simplicity, we have made the following assumptions:

(1) Heat exchange happens only through the top and bottom surfaces of the steel ingot. The heat transmission to the ingot ends is neglected. Moreover, a temperature gradient exists only in the direction vertical to the top and bottom surface. Hence,

a 3-dimensional heat transmission problem is simplified to a one-dimensional problem.

(2) The thermal parameters such as the heat transmission coefficient and the thermal capacity are determined by the type of steel and are functions of temperature. In a small time interval, the variation of temperature is small enough for the temperature to be considered as constant.

(3) All the ingots in the furnace have the same geometric size.

Assume the cross-section of steel ingot is 2Hx2H, as in Fig. 1. Then the heat transmission process can be described by the following differential equation

$$\frac{\partial T(x,t)}{\partial t} = a \frac{\partial^2 T(x,t)}{\partial^2 x}$$

In the equation: $a = \frac{K}{C\rho}$

$T(x,t)$ - temperature of certain point in the ingot at time t;

t - time;

a - heat spread coefficient;

C - thermal capacity;

ρ - density of steel ingot.

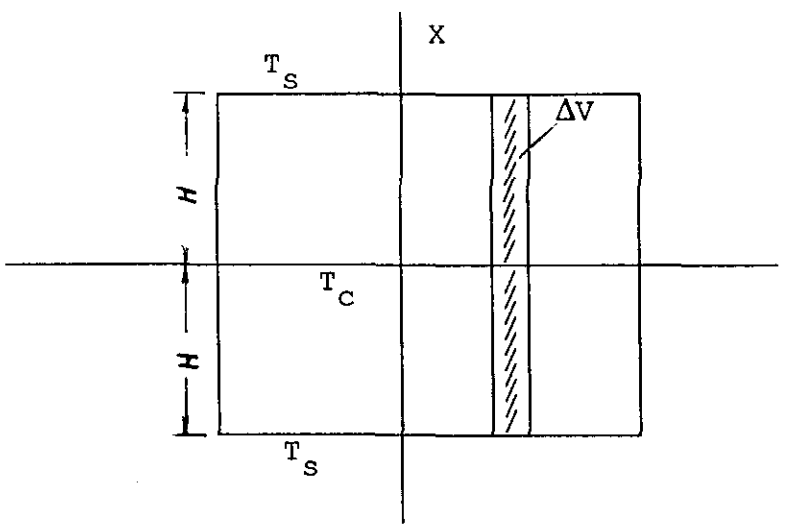

Fig. 1. Cross Section of the steel ingot

In practice, the thermal states which are of interest to us for computer control are steel ingot surface temperature T_S and ingot centre temperature T_C. To obtain recursive formulae of $T_S(n)$ and

$T_c(n)$, discretization of eq.(1) is necessary.
We propose to use a quadratic curve to represent the temperature distribution along the x axis as in Fig. 1. This can be proved mathematically and the numerical solution of computer simulation agrees with the assumption.

Using the above assumption:
Assume at a certain time instance the temperature inside the ingot along x is T(x), using the above assumption:

$$T(x) = a_o + bx^2 \qquad 0 \le x \le H$$

in the equation $a_o = T_c$, $b = (T_s - T_c)/H^2$
So from equation (1) we obtain

$$\dot{T}_c = \frac{2a}{H}(T_s - T_c) \tag{2}$$

The discrete formula can be obtained by discretization of eq. (2). Moreover, the boundary conditions can be deduced from the heat balance equation; the heat transmission between the steel ingot and gas is mainly in radiation form while, by neglecting convective heat transfer, the flow of heat q_r described by eq.(3).

$$q_r = \varepsilon\sigma[(T_f + 273)^4 - (T_s + 273)^4] \tag{3}$$

ε - blackness coefficient of heated
σ - s-b constant
T_F - furnace temperature (C°)
T_s - surface temperature of ingot (C°)

Assume a tiny column in the steel ingot which has cross section S and volume ΔV so that $\Delta V = 2HS$.
The heat quantity absorbed by the ingot at time Δt is

$$Q_1 = S\varepsilon\sigma[(T_f + 273)^4 - (T_s + 273)^4]\Delta t \tag{4}$$

Meanwhile, the heat quantity Q which is necessary for the ingot temperature to rise, is given in equation (5).

$$Q_2 = Q''_2 - Q'_2 \tag{5}$$

where Q_2' , Q_2'' are the heat quantities contained by the tiny column at time t and t+Δt, respectively

$$Q_2' = \int_{\Delta V} C\rho T(x)\,dv = \frac{C\rho SH}{3}\,[2T_c' + T_s'] \tag{6}$$

$$Q_2'' = \frac{C\rho SH}{3}\,[2T_c'' + T_s''] \tag{7}$$

and T_c', T_s' and T_c'' , T_s'' are the centre and surface temperatures of the small column at time t and t+Δt, so that ,

$$Q_2 = \frac{C\rho SH}{3}\,[2\Delta T_c + \Delta T_s] \tag{8}$$

By the dynamic heat balance equation: $Q_1 = Q_2$ we obtain:

$$\frac{C\rho H}{3}\,[2\,\frac{\Delta Tc}{\Delta t} + \frac{\Delta Ts}{\Delta t}] = \varepsilon\sigma[(T_f + 273)^4 - (T_s + 273)^4] \tag{9}$$

when Δt tends to zero,

$$2\dot{T}_c - \dot{T}_s = \frac{3\varepsilon\sigma}{C\rho H}\,[(T_f + 273)^4 - (T_s + 273)^4] \tag{10}$$

Substitute eq. (2) into (10)

$$\dot{T}_s = \frac{3\varepsilon\sigma}{C\rho H}\,[(T_f + 273)^4 - (T_s + 273)^4]\,\frac{4a}{H}\,(T_s - T_c) \tag{11}$$

Discretization of eq. (2) and (11)

$$T_m(n+1) = T_s(n) + A_1\,\{[T_f(n)+273]^4 - [T_s(n)+273]^4\} - A_2[T_s(n) - T_c(n)] \tag{12}$$

$$T_s(n+1) = T_s(n) + A_1\,\{(T_f(n+1) + 273]^4 - [T_m(n+1) + 273)^4]\} - A_2[T_s(n) - T_c(n)] \tag{13}$$

$$T_c(n+1) = \{T_c(n) + \frac{A_2}{2}[T_s(n) - T_c(n) + T_s(n+1)]\}/(1+\frac{A_2}{2})$$

$$\text{where } A_1 = \frac{3\varepsilon\sigma}{C\rho H} \quad ; \quad A_2 = \frac{4a}{H} \; ; \tag{14}$$

$T_m(n+1)$ is a medium variable, $T_s(n+1)$ is the one-step-ahead prediction of the ingot surface temperature, $T_c(n+1)$ is the one-step-ahead prediction of the ingot centre temperature. The recursive formulae of the steel ingot heating model are equation (12) to equation (14), where only T_f is the measured value, the other variables are calculated values.

The surface and centre temperatures of the steel ingot at a certain time in the heating process can be obtained by using this mathematical model when the ingot size, type and parameters concerned are given. When the estimates of these two temperatures are available, the important thermal parameters such as average temperature, the temperature difference of ingot surface and centre can be calculated.

3. MODEL VALIDATION BY SIMULATION AND EXPERIMENTAL TEST

In the last section, a steel ingot heating process model has been established. This model is computationally simple compared with other methods [4] [5]. The thermal states of the steel ingot needed can be given by computer for different steel ingot sizes, types and operation conditions (time in furnace, gas temperature at different parts of the furnace). The simulation curve of a carbon steel ingot is shown in Fig. 2. The simulation of the steel ingot heating process provides the numerical value basis for the instruction for the off-line optimization strategy.

To verify the precision of this model, an ingot heating test has been performed on a furnace in the Xining Steel Plant. The centre temperature of the steel ingot was measured by a thermocouple plugged into a small hole drilled through the top of the ingot.

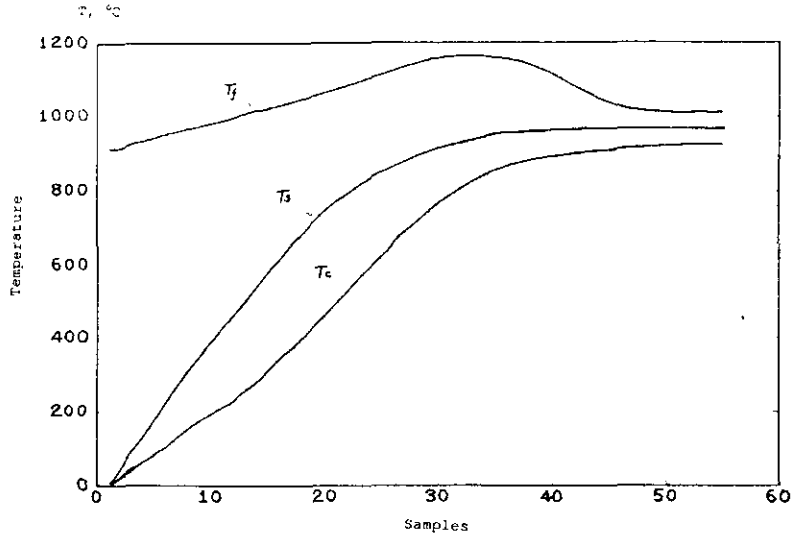

Fig. 2. The dynamic response of ingot temperature T_f, T_s, T_c. (Ingot size 275 x 275 x 1040 mm)

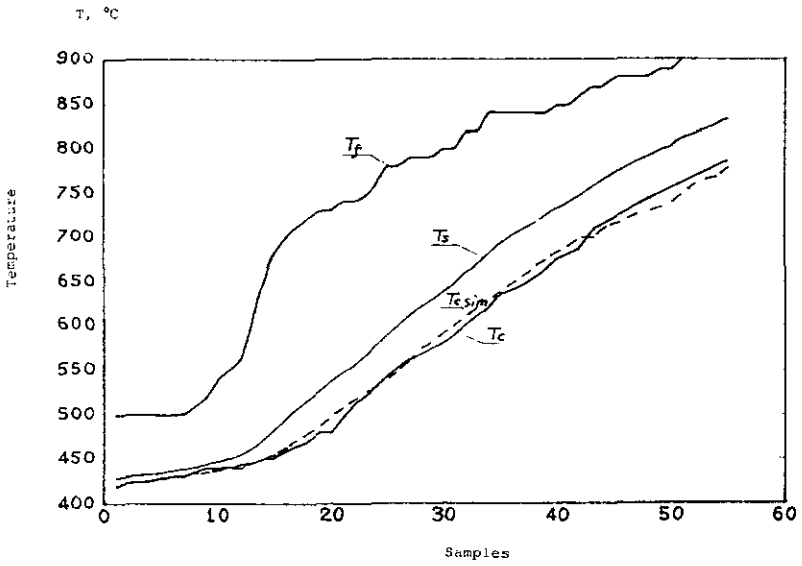

Fig. 3. The measured data and model output value.

The furnace temperature and ingot centre temperature were recorded. Meanwhile, the steel type, ingot size and furnace temperature was given to the computer in order to determine the parameters of the model. Hence the estimation value of the steel ingot temperature at various sample times can be obtained. The estimated values and tested data are shown in Fig. 3.

The dotted line shows the estimation value given by the model, the

solid line is the measured value. The error between model output and measured value is less than 17°C, i.e. less than 2 percent over the whole measuring range.

The test shows that the precision of the estimation is good enough for industrial application, where the tolerance of the estimation error of temperature is 50°C.

4. MODEL-BUILDING BY SYSTEM IDENTIFICATION

In previous sections, we built a mathematical model based on physical laws. In that case, the model is derived only from physical knowledge. In principle, there are two different ways in which models can be obtained: One is to derive the model from prior knowledge, e.g. by means of physical laws, the other is by identification which is an experimental approach to process-modelling.

An approximate linear time-invariant model of the steel ingot heating process is obtained by system identification. We use two ways to obtain models:

(i) Equation error method (EEM)

(ii) Output error method (OEM)

Both are based on the principle of least squares.

We shall introduce the two methods briefly. For the purpose of identification, the process is typically assumed to be a linear time-invariant, discrete time system, described by a difference equation. In the noise free case the process is given as

$$A^{\circ}(z^{-1})\ y^{\circ}(k) = B^{\circ}(z^{-1})\,u(k) \qquad (15)$$

where $y^{\circ}(k)$ and $u(k)$ are the process output and input at sample time k; $A^{\circ}(z^{-1})$ and $B^{\circ}(z^{-1})$ are polynomials of z^{-1}, the backward time-shift operator, and

$$A^{\circ}(z^{-1}) = 1 + a_1^{\circ}\ z^{-1} + \ldots + a_n^{\circ}\ z^{-n}$$

$$B^{\circ}(z^{-1}) = b_0^{\circ} + b_1^{\circ}\ z^{-1} + \ldots + b_n^{\circ}\ z^{-n}$$

n is called the order of the model.

The rational function

$$H^{\circ}(z^{-1}) = \frac{B^{\circ}(z^{-1})}{A^{\circ}(z^{-1})} \tag{16}$$

is called transfer function of the process.

In order to have a more realistic model, one can introduce the process noise. A natural way to do this is to assume that the output is disturbed by an additive noise,

$$y(k) = y^{\circ}(k) + e_0(k) \tag{17}$$

where $y^{\circ}(k)$ is the noise-free output, given by (15), $\{e_0(k)\}$ is assumed to be white noise or filtered white noise. Hence we have the so-called output error structure of the process.

$$y(k) = \frac{B^{\circ}(z^{-1})}{A^{\circ}(z^{-1})} u(k) + e_0(k) \tag{18}$$

and

$$\hat{e}_0(k) = y(k) - \frac{B(z^{-1})}{A(z^{-1})} u(k) \tag{19}$$

where (19) is the output error model, $A(z^{-1})$ and $B(z^{-1})$ has the same structure as $A^{\circ}(z^{-1})$ and $B^{\circ}(z^{-1})$ resp., $\hat{e}_0(k)$ is the output error.

Denote Z^N as the input/output data sequence collected from the experiments:

$$Z^N = y(1), u(1), \ldots, y(N), u(N) \tag{20}$$

where N is the number of samples.

Let θ denote the parameter vector of model (19):

$$\theta^T = (a_1, a_2, \ldots, a_n, b_0, b_1, \ldots b_n) \tag{21}$$

The least-squares principle is used to determine an estimate of θ. The loss function is given by

$$J_0(Z^N, \theta) = \frac{1}{N-n} \sum_{k=n+1}^{N} \hat{e}_0^2(k,\theta) \tag{22}$$

where

$$\hat{e}_0(k,\theta) = y(k) - H(z^{-1},\theta)u(k) \tag{23}$$

and $H(z^{-1},\theta) = \frac{B(z^{-1})}{A(z^{-1})}$

The estimate $\hat{\theta}$ is obtained by

$$\text{min. } J_0(Z^N,\theta) \tag{24}$$

Then the estimate of transfer function is $\hat{H}(z^{-1}) = H(z^{-1},\hat{\theta})$. This method is called output error method.

If we use the estimated model to simulate the process, using the same input as in the estimation, the simulated output is given by

$$\hat{y}(k) = \hat{H}(z^{-1})u(k) \tag{25}$$

We see that $\hat{e}_0(k)$ in (23) becomes the simulation error. Therefore, the output error model is obtained by minimizing the simulation error (in the least-squares sense) and the model is mostly suited for the simulation; here the simulation means calculating the output, based on the model and the previous and present input.

Note that (24) is a non-linear least squares minimization problem; this is because the error is non-linear in the parameters of $A(z^{-1})$ (see (19)). The output error method is numerically involved, and it can be solved by some hill climbing iteration procedure, for example, Newton- Raphson method.

The process and the model of output error method is given in Fig. 4.

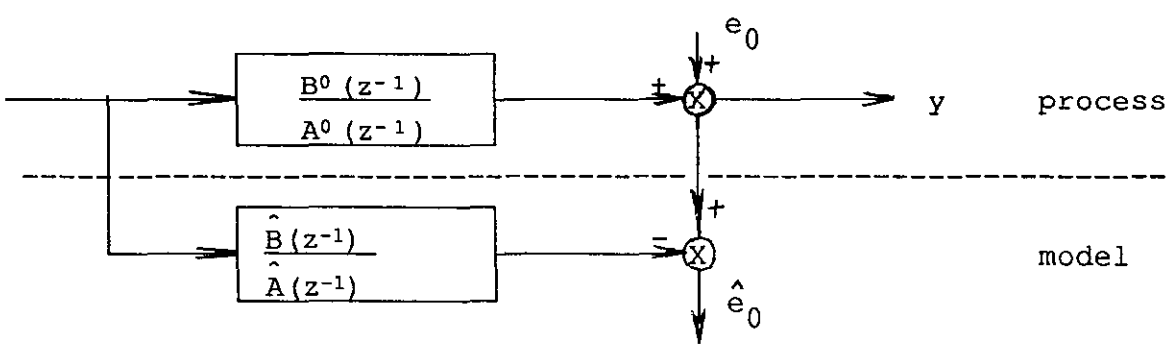

Fig. 4. The process and the model for the output error method.

The most well known method is the so-called "least squares method", which we should call here the "equation error method". The reason for this will become clear later on. This method is based on another way of introducing the disturbance into the noise-free process (15).

Now, we assume that the process is disturbed by equation noise, then (15) becomes

$$A^0(z^{-1})y(k) = B^0(z^{-1})u(k) + e_E(k) \tag{26}$$

where $\{e_E(k)\}$ is the equation noise.
Again, we assume that $\{e_E(k)\}$ is either white noise or filtered white noise.
The equation error model is

$$\hat{e}_E(k) = A(z^{-1})y(k) - B(z^{-1})u(k) \tag{27}$$

where $\hat{e}_E(k)$ is the equation error.
Now, let us write (27) in terms of the parameters:

$$y(k) + a_1y(k-1) + \ldots a_ny(k-n) =$$

$$b_0u(k) + b_1u(k-1) + \ldots + b_nu(k-n) + \hat{e}_E(k) \tag{28}$$

Putting the data sequence Z^N into this model, we get

$$Y = \Omega(u,y).\theta + \hat{E}_E \tag{29}$$

where

$$Y^T = [y(n+1)\,y(n+2) \ \ldots \ y(N)] \tag{30}$$

$$\hat{E}^T_E = [\hat{e}_E(n+1)\ \hat{e}_E(n+2) \ \ldots \ \hat{e}_E(N)] \tag{31}$$

$$\theta^T = [b_0,\ b_1,\ \ldots\ b_n,\ -a_1\ -a_2\ \ldots\ -a_n] \tag{32}$$

$$\Omega(u,y) = \begin{bmatrix} u(n+1) & \ldots & n(1) & . & y(n) & \ldots & y(1) \\ . & & . & . & . & & . \\ . & & . & . & . & & . \\ . & & . & . & . & & . \\ u(N) & \ldots & u(N-n) & & y(N-1) & \ldots & y(N-n) \end{bmatrix} \tag{33}$$

The equation error least squares method is to determine $\hat{\theta}$ (the

estimate of θ) by minimizing the loss function

$$J_E(Z^N,\theta) = \frac{1}{N-n} \sum_{k=n+1}^{N} \hat{e}_E^2(k) = \frac{1}{N-n} \hat{E}_E^T \hat{E}_E \qquad (34)$$

It is well known that this is a linear least squares problem. The solution is explicit and is given by

$$\hat{\theta} = [\Omega^T(u,y).\Omega(u,y)]^{-1} \Omega^T(u,y) Y \qquad (35)$$

If $[\Omega^T.\Omega]$ is non-singular, we get the unique solution of $\hat{\theta}$. The reason for the explicit solution of (35) is that the equation error is linear in the parameters of the model (see (27)), and the quadratic error criterion (34) is used.

Let us calculate the one-step prediction, based on the model (28) and previous input, - output and present input

$$\hat{y}(k) = - a_1 y(k-1) - \ldots - a_n y(k-n) + b_0 u(k) + b_1 u(k-1) + \ldots + b_n u(k-n) \qquad (36)$$

then (28) becomes

$$\hat{e}_E(k) = y(k) - \hat{y}(k).$$

We can say that the equation error model will give the best one-step ahead prediction (in the least squares sense). The equation error process and the model are given in Fig. 5.

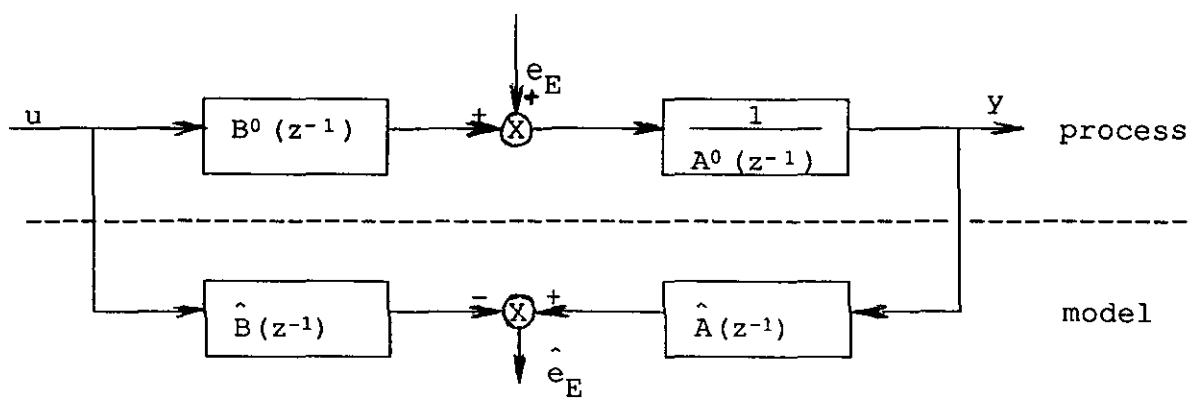

Fig. 5. Process and model for equation error method.

Summarizing: the output error model is obtained by minimizing the simulation error, the equation error model is obtained by minimizing the one- step prediction error; and the computation of the output error method is much more complicated than the equation error method.
Before we estimate the parameters, the order n should be determined.
Least squares estimators deal with the minimization of a quadratic loss function for a given order. The idea of using the loss function for the determination of the parameters can be extended for selection of the order of the model within the chosen model set. This approach provides a family of loss function tests. The usual test quantities are

$$V = \frac{1}{N} \hat{\underline{e}}^T \hat{\underline{e}}$$

where $\hat{\underline{e}}$ is the error of the process dynamics which is being modelled. The power of these signals $\hat{\underline{e}}$ is dependent on the model order. We can observe that V will decrease for increasing order, as for too low model orders not enough degrees of freedom have been inserted in the model.
A simple order test can be constructed using the by-products of the estimation algorithm for the calculation of the loss function, see Fig. 16.

Note that the errors used here are always the output errors (simulation errors) irrespective which model is concerned, because our intended use of the model is simulation.

The experimental data are given in table 1.

Table 1

	T_f	T_{ct}	T_{cM}	T_s	ΔT_c
1	500	420	421	436	-1
2	500	425	423	430	2
3	500	425	425	432	0
4	500	425	427	433	-2
5	500	430	428	435	2
6	500	430	430	437	0
7	500	430	432	438	-2
8	510	435	433	441	2
9	520	440	435	442	5
10	540	440	437	447	3
11	550	440	440	451	0
12	560	440	443	455	-3
13	600	445	446	461	-1
14	650	450	450	471	0
15	680	450	456	483	-6
16	700	460	463	494	-3
17	710	465	471	505	-6
18	720	470	479	516	-9
19	730	480	488	527	-8
20	730	480	497	537	-12
21	740	495	506	547	-11
22	740	510	515	556	-5
23	745	520	524	566	-4
24	760	530	533	577	-3
25	780	540	543	589	-3
26	780	550	553	599	-3
27	790	560	562	610	-2
28	790	565	572	620	-7
29	790	575	582	629	-7
30	800	580	591	639	-11
31	800	590	601	648	-11
32	820	600	610	660	-10
33	820	610	619	669	-9
34	840	620	629	681	-9
35	840	635	639	692	-4
36	840	640	648	701	-8
37	840	645	657	709	-12
38	840	655	666	717	-11
39	840	665	675	724	-10
40	850	675	683	732	-8
41	850	680	691	739	-11
42	860	690	699	748	-9
43	870	707	700	757	7
44	870	714	710	764	-4
45	880	722	715	773	-7
46	880	729	720	780	-9
47	880	736	725	786	-11
48	880	743	730	792	-13
49	890	750	735	799	-15
50	890	757	740	805	-17
51	900	763	750	812	-13
52	900	769	760	818	-9
53	900	775	765	824	-10
54	900	781	770	829	-11
55	900	787	780	833	7

T_f - furnace temperature

T_{ct} - Centre temperature test data

T_{cM} - Centre temperature given by the model

T_s - Surface temperature of ingot

ΔT_c - $(T_{ct} - T_{cm})$

Before the identification the data are modified by subtracting the DC component (420°) from the experimental data. The input variable is furnace temperature and the output variable is the centre temperature of the steel ingot. To examine the correctness of the model, simulation is used and for this problem, the system identification and simulation were implemented on a PC, using the system identification toolbox, which is a collection of MATLAB functions for all phases of the system identification process.

The result of the computation and simulation are shown in Fig. 6 - 16.

Fig. 6 shows the responses of the true system and of the estimated model when using the equation error method (EEM) with model order n=4, delay=1. Simulation error of 4th equation error model are shown in Fig. 7.
Fig. 8, 9, 10 show T_f, T_c, simulated T_c, simulation error and zero-pole plot of 2nd order OE model.
Fig. 11, 12, 13 show T_f, T_c simulated T_c, simulation error and zero-pole plot of 3rd order OE model.
The responses of T_c and simulated T_c of physical model are shown in Fig. 14. The errors of 3rd order OE model and physical model are shown in Fig. 15 .
Fig. 16 showsthe loss functions of EE, OE and physical models.

From the plots of loss functions, we see that second order equation error and output error models already give better results than the physical model; output error models are better than the equation error models for the simulation purpose, because the equation error models are not obtained by minimizing the simulation error loss function.

Comparison Between Physical Model-building and System Identification

Model-building using physical laws requires knowledge and insight into the process. The main problem when making a mathematical model is to find the states of the system. The state variable essen-

tially describes storage of the energy in the system.
Typical variables are chosen as furnace temperature, ingot surface temperature and ingot centre temperature.
The relationship between the states is determined using energy balance equation.
The advantage of model-building from physics is that it gives insight; also the different parameters and variables have physical interpretations.
In the economical aspect, this method is cheaper than the system identification method, because it is often difficult and costly to do experiments with industrial processes.
The drawback is that it may be difficult and time consuming to build the model from first principles.
Model-building by identification when investigating a process is based on experimental data; where the a priori knowledge is poor, it is difficult to build the model from physical laws. Then it is reasonable to use system identification. The simulation results show that the steel ingot heating model obtained by the equation error method or output error method gives higher precision than the mathematical model obtained by physical laws. But if the type or size of the steel ingot are changed, new individual experiment tests are needed for different kinds of steel ingots. So if it is possible, the best way is to combine the two methods.

5. CONCLUSIONS

A mathematical model-building based on the heat transmission theory and using a quadratic curve to represent the temperature distribution in a steel ingot is obtained. The simple recursive model of the steel ingot heating process, with high calculating speed has been developed, which describes the thermal state of steel ingot in the whole heating process. The experimental test shows that the quality of the model is good enough for industrial application.

In different ways, the steel ingot heating model also has been obtained by experimentation on the process. The equation error method and the output error method have been used for analysing data obtained from experiments. Simulation results show that the

steel ingot heating model obtained by system identification gives better estimation of the characteristics and higher precision than model-building using physical laws.

The advantage of model-building from physics is that it gives insight; also the different parameters and variables have physical interpretations. But it may be difficult and time consuming to build the model from first principles.

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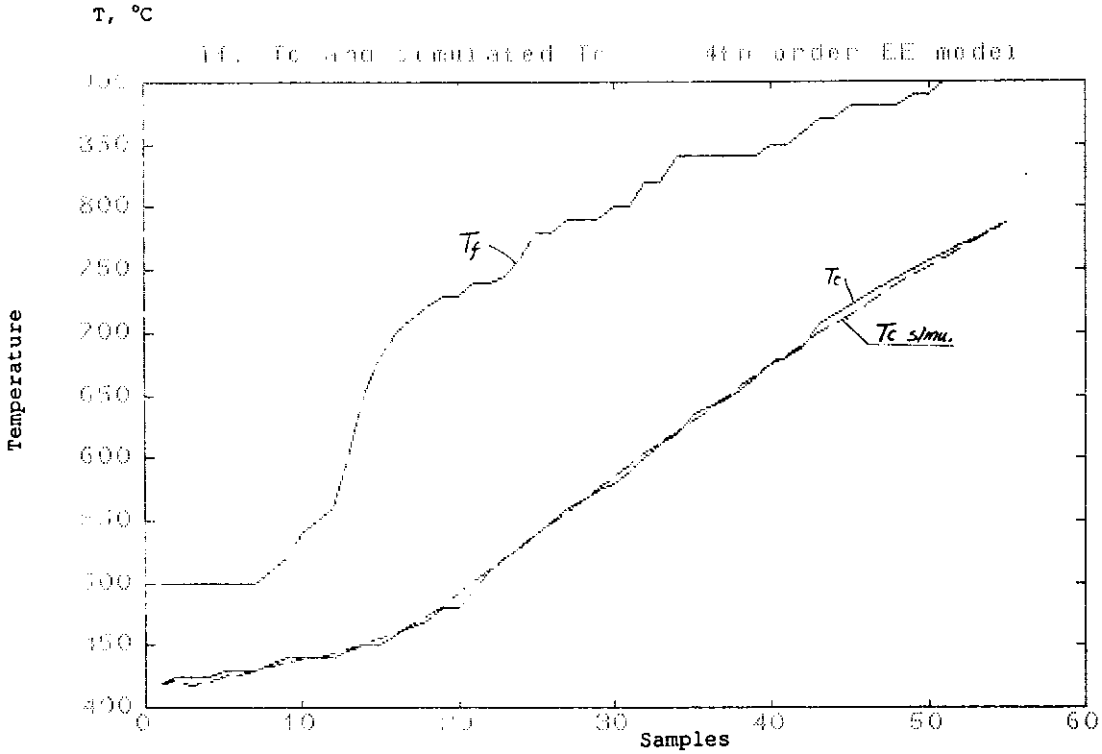

Fig. 6. T_f, T_c and simulated T_c. 4th order EE model

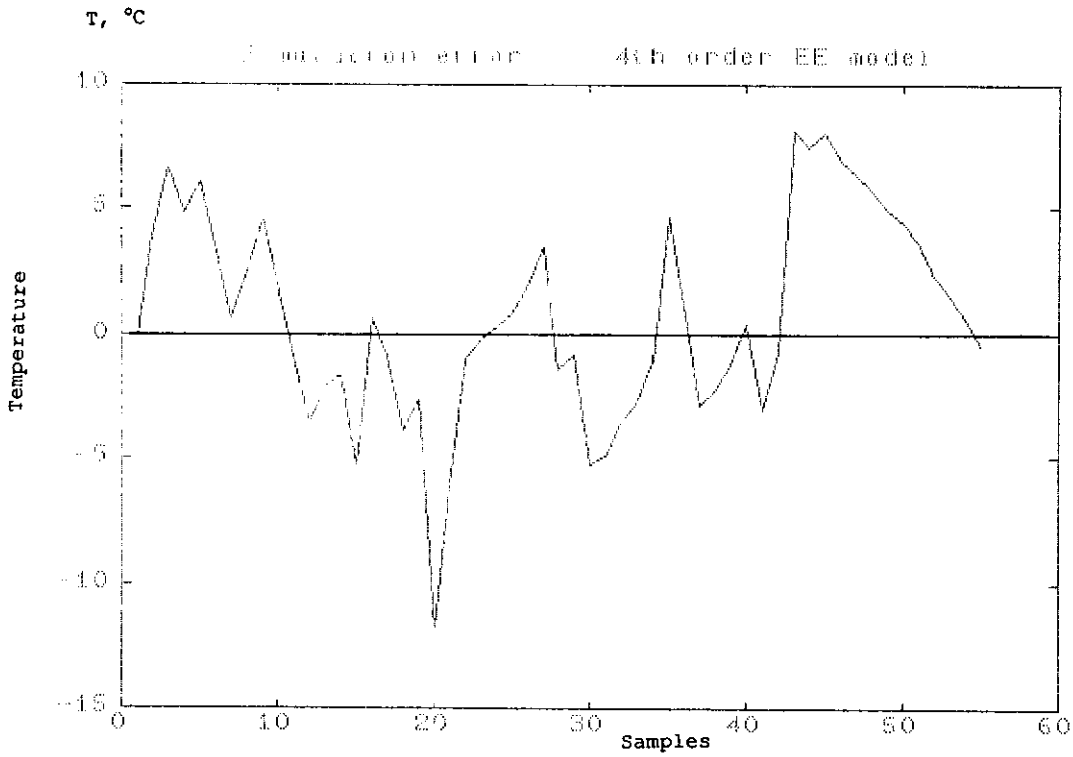

Fig. 7. Simulation error of 4th order EE model.

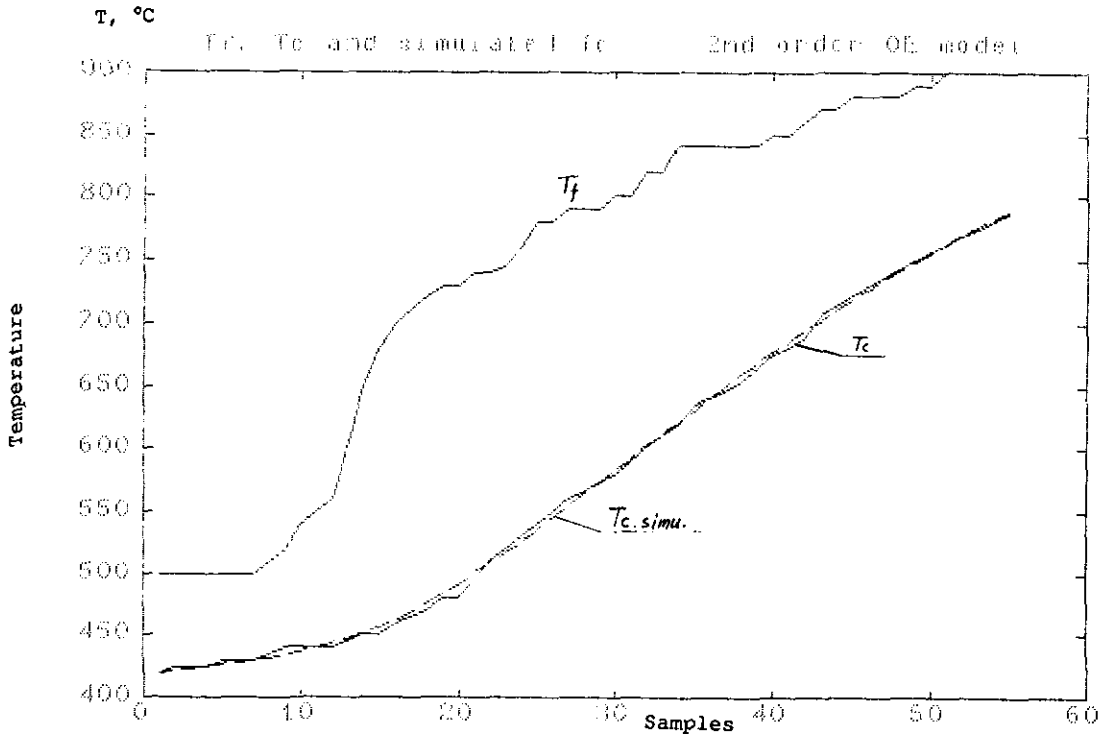

Fig. 8. T_f, T_c and simulated T_c. 2nd order OE model.

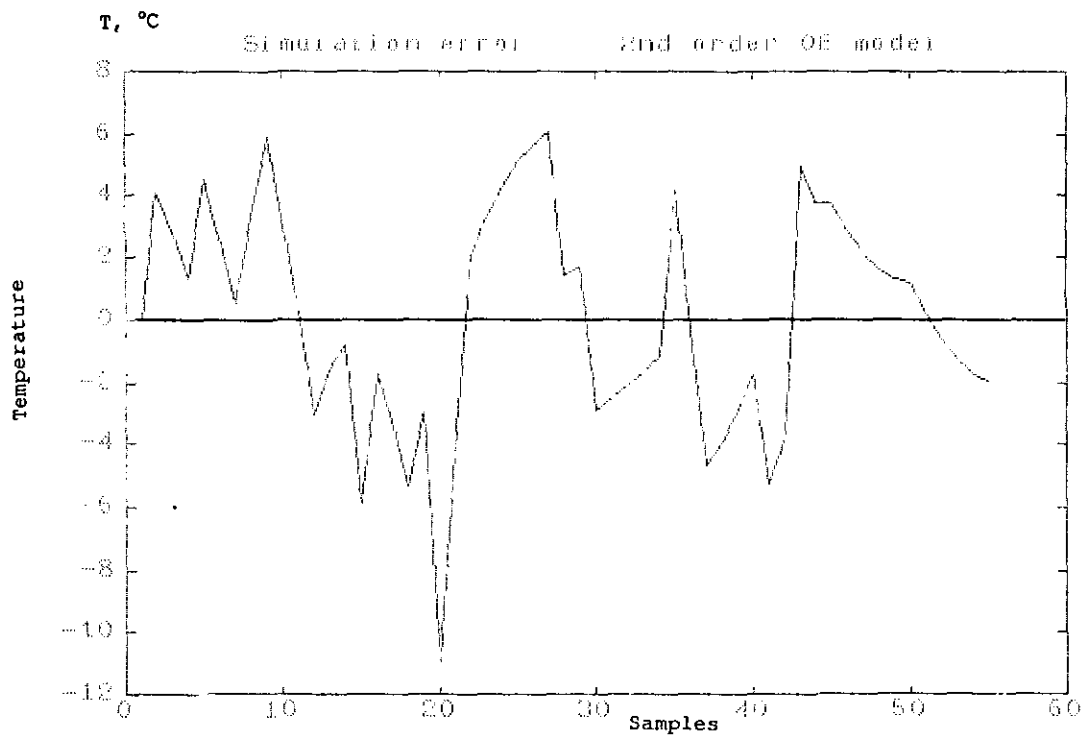

Fig. 9. Simulation error. 2nd order OE model.

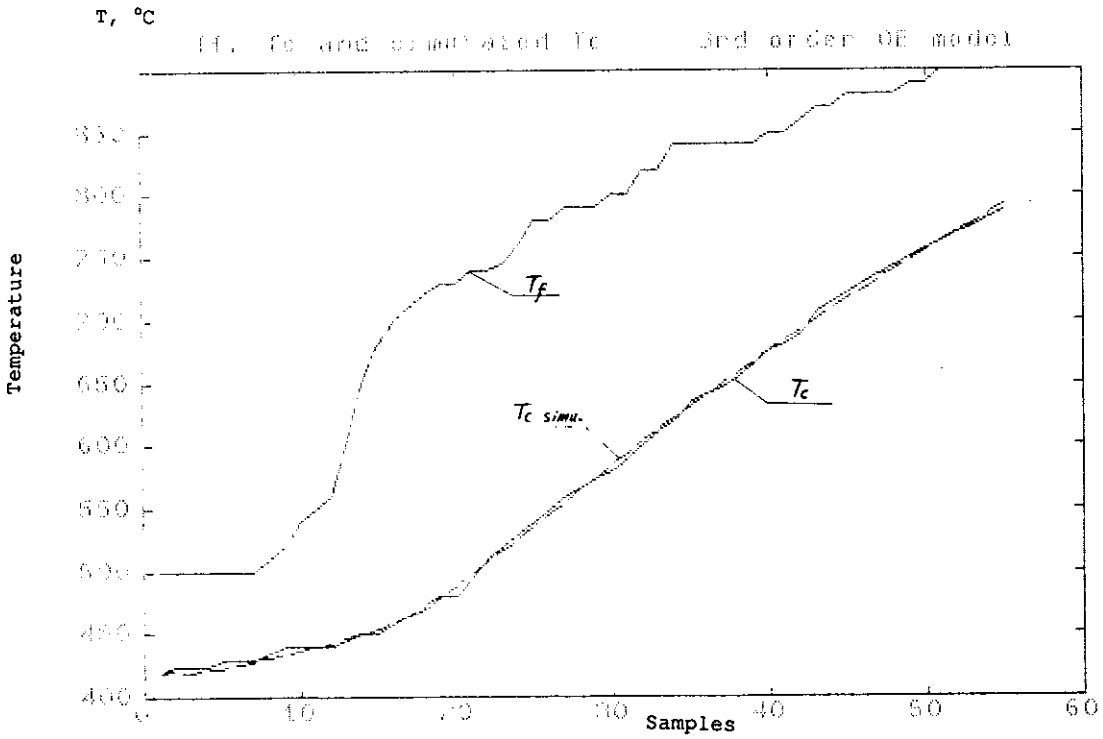

Fig. 11. T_f, T_c and simulated T_c. 3rd order OE model.

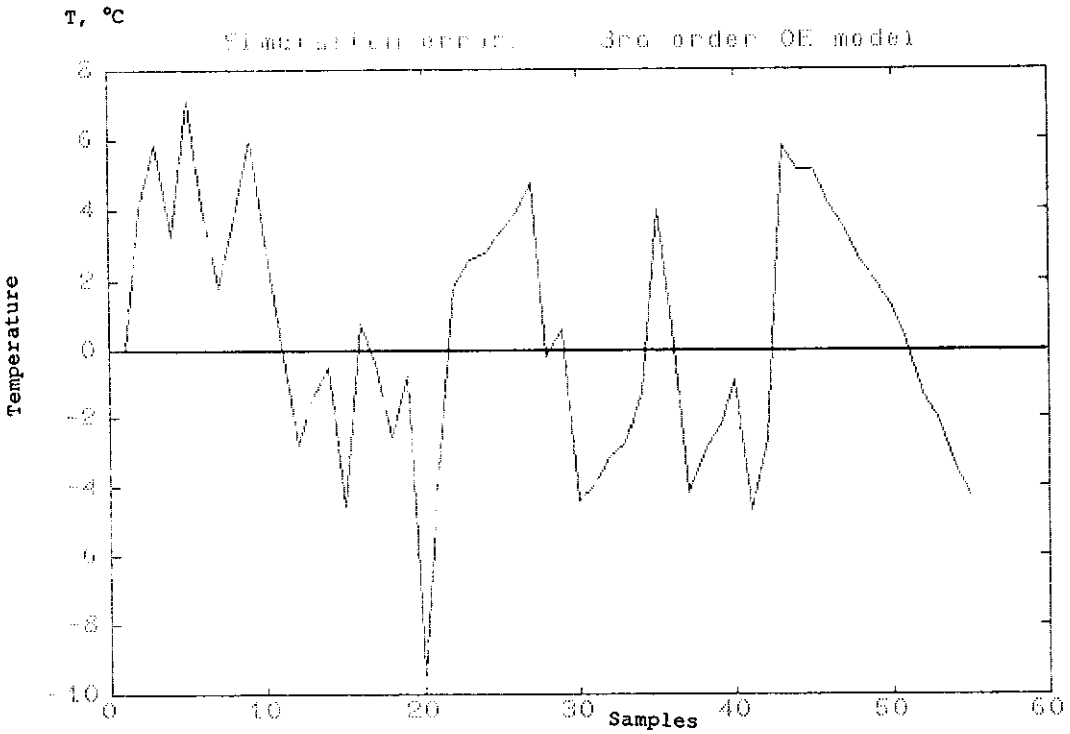

Fig. 12. Simulation error of 3rd order OE model.

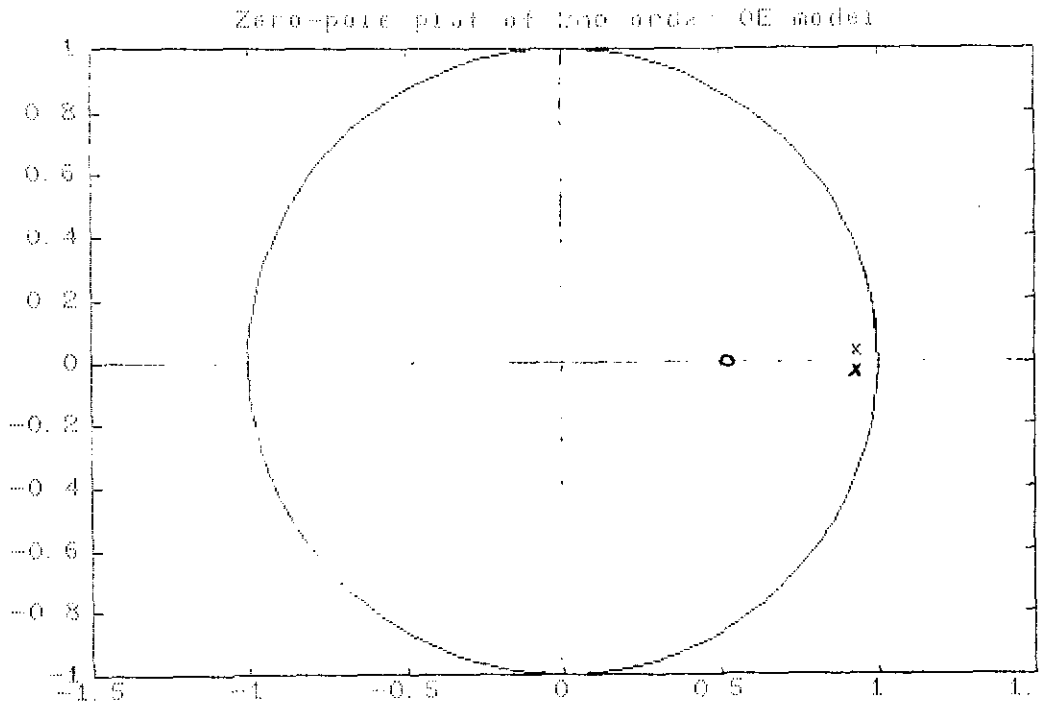

Fig. 10. Zero-pole plot of 2nd order OE model.

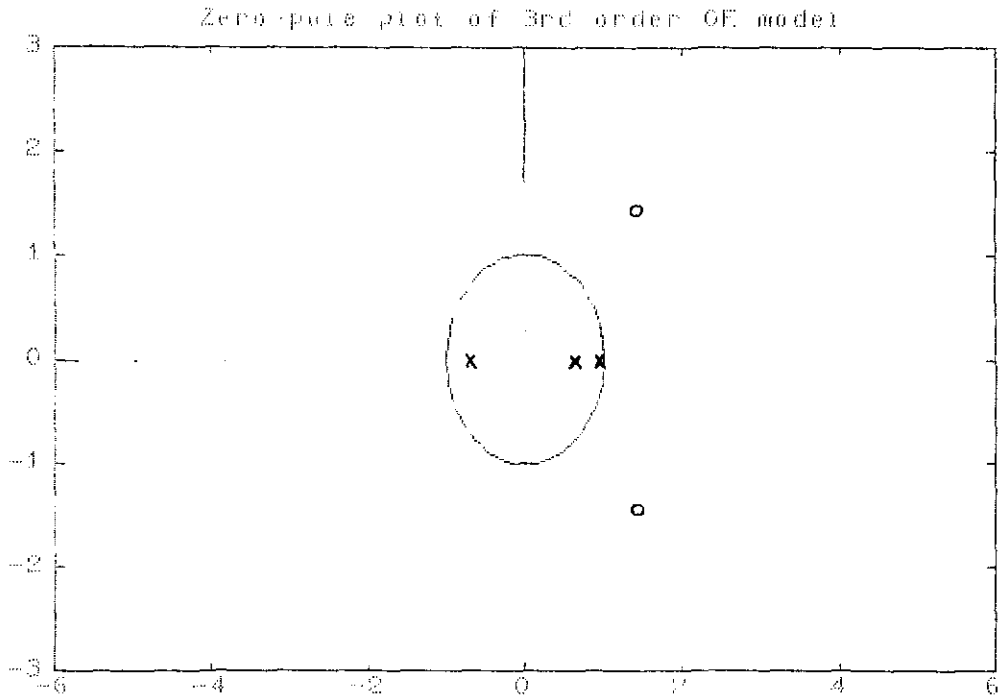

Fig. 13. Zero-pole plot of 3rd order OE model.

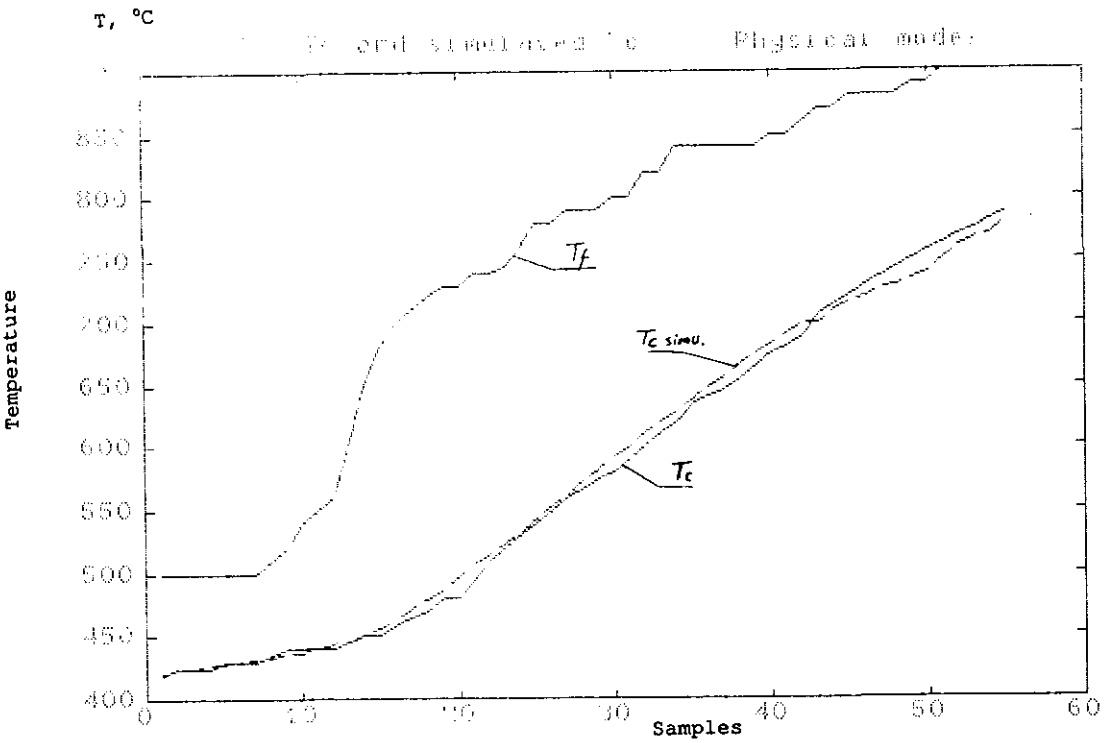

Fig. 14. T_f, T_c and simulated T_c. Physical model.

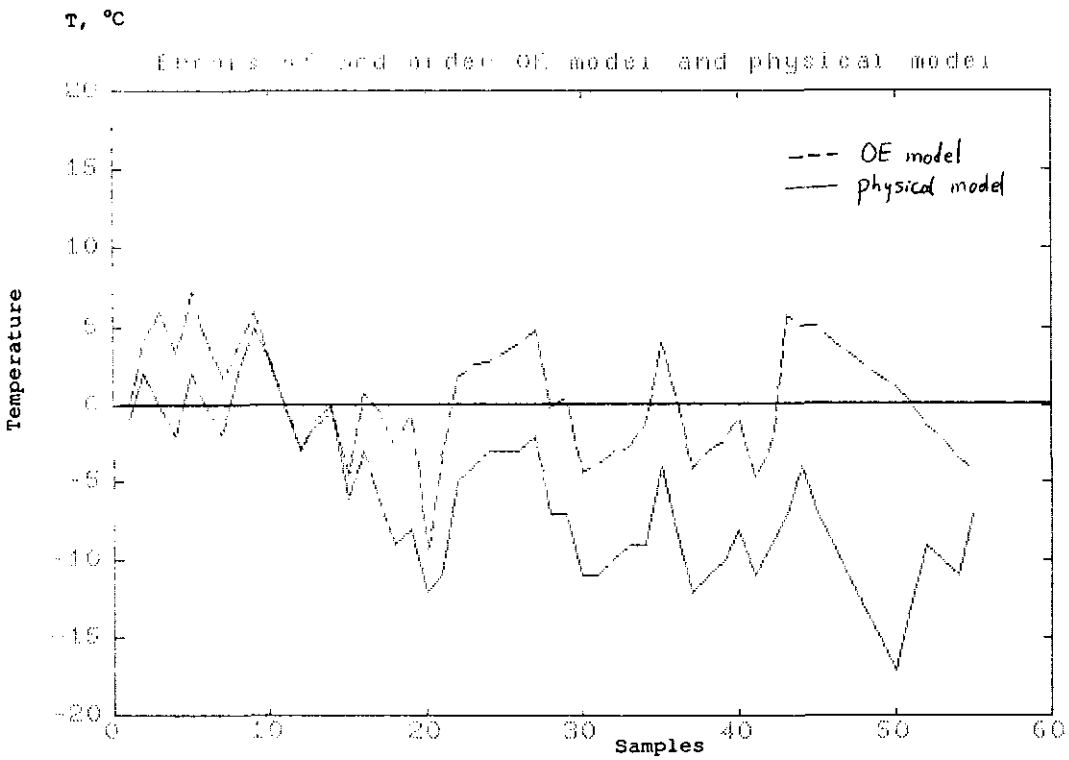

Fig. 15. Errors of 3rd order OE model and physical model.

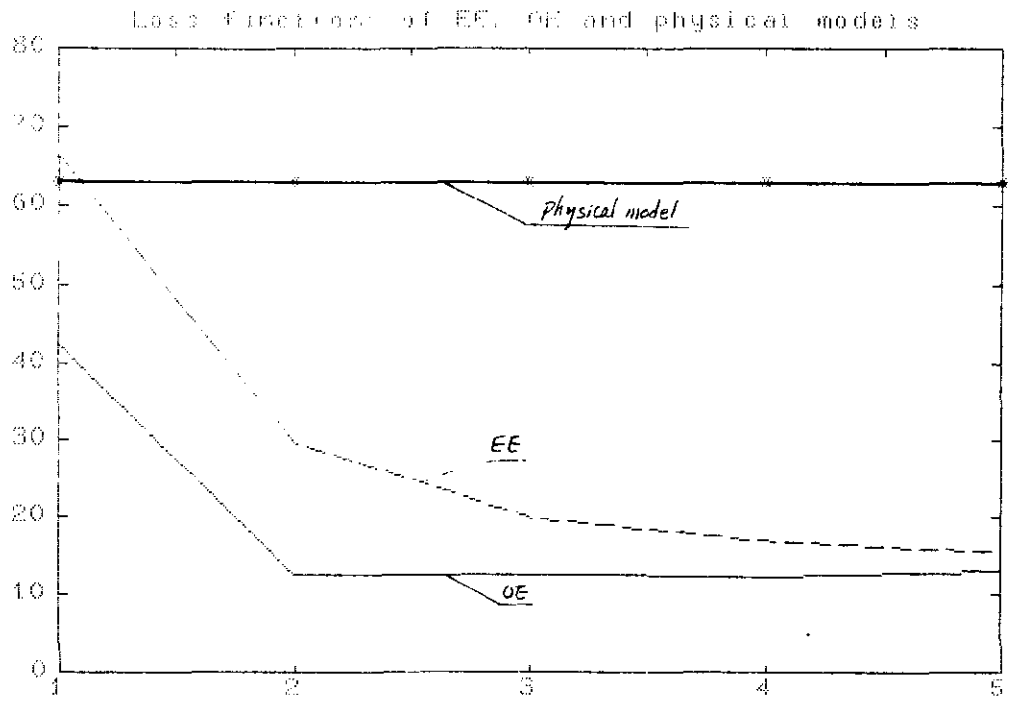

Fig. 16. Loss functions of EE, OE and physical models.

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