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Application of Sequential Quadratic Programming Method to Temperature Distribution Control in Reactor Furnace

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In reactor furnace, due to high temperature and high pressure, data can be measured only near the furnace wall. In this paper, the way to estimate temperature distribution in a reactor furnace using measured data near the furnace walls and to control temperature distribution to the desired temperature distribution was studied. In the estimation, SQP method is employed using measured data near the furnace walls. As the result, the whole temperature distribution in a furnace could be obtained from such limited data. Furthermore, to control the temperature distribution in a reactor furnace, gas flow from multiple tuyeres and supplying material for controlling temperature distribution in a reactor furnace were determined by the SQP method. It was shown that temperature distribution in a furnace was regulated to achieve various desired distribution. Thus, it was verified that complicated temperature distribution in a reactor furnace could be controlled by combining furnace simulation and SQP method.

1 Introduction

A reactor furnace such as a blast furnace has been playing a vital role in metal industries. Based on the improvements of furnace facilities, the size of a furnace has become remarkably enlarged. As well known, internal phenomena of a reactor furnace such as a blast furnace are complex[1]−[4] , and the operation of a reactor furnace is still depending on experiences and intuitions of the skilled operators.

Since various changeable factors, such as gas flow, chemical reactions, burn-through and anastomoses of iron ores and movement of filling materials in a furnace are entangled intricately, the inside of a reactor furnace remains as a grey box. Meanwhile, stable and low cost operations are required in the actual work front. Moreover, in the future, automated furnace operation is expected to cope with the decreasing number of skilled operators and the difficulty in finding their successors.

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In this research, we pursue the construction of control system for the reactor furnace. In other words, the problem is matching temperature distribution in reactor furnace to desired temperature distribution by multiple tuyeres as boundary conditions.

As described above, due to the complexity of inner furnace phenomena such as chemical reactions, high pressure and high temperature in a furnace, variables of only near the furnace wall can be measured. Therefore, we tried to estimate the inner furnace temperature distribution from measured data of sensors equipped at near the furnace wall. In the estimation, the estimated temperature distribution in a reactor furnace is tried to match to the measured boundary data by regulating blowing of multiple tuyeres at a furnace bottom. After the estimation, control of the inner furnace temperature distribution is tried by regulating conditions for gas blowing and burden supply. The sequential quadratic programming method (SQP method) is used both for the estimation and the control of the inner furnace temperature distribution.

For these purposes, a simplified furnace simulator for inner furnace gas flow and temperature distribution was developed, which uses boundary conditions as the control variables. This simulator is simplified from previous studies[5]−[7] to attain the swift computation preserving the principal parts of calculation for reaction and heat transfer phenomena in a reactor furnace.

The simulator is combined with a SQP method. That is, the temperature distribution in a reactor furnace is estimated by the combination of a SQP method and the furnace simulator using measured boundary values of a furnace. Here, the measured boundary data are temperature, pressure and gas flow at near a furnace wall. Temperature distribution in a reactor furnace is controlled conforming the estimated temperature distribution to the desired one regulating blowing conditions in multiple tuyeres at the furnace bottom and supplying materials at the top. Here, again a SQP method is used.

In addition, it is attempted to upgrade of reactor furnace model in order to describ a production of the pig-iron. Therefore, solid flow distribution is added to the existing reactor furnace model. A production of the pig-iron is described by this solid flow distribution.

2 Control Method of Temperature Distribution

In the following, the control method of temperature distribution in a reactor furnace is described. This method is shown in Fig. 1. As shown in the figure, there are two parts, the estimation of temperature distribution and the control of it.

First, estimation part is processed. To know the temperature distribution in a reactor furnace, the mathematical model is applied using total gas flow, material charge condition and boundary conditions as its input. The mathematical model is formed by reference[8][9]. The temperatures calculated by mathematical model are compared with the measured temperatures, gas volumes from multiple tuyeres are determined in order to reduce the error between these two values. Thus, the gas volume from multiple tuyeres is calculated. The SQP method is used to estimate temperature distribution. Descriptions of the mathematical model are written in an appendix.

Next, control part is processed. Operations of a furnace in order to conform estimated temperature distribution of a reactor furnace to the desired temperature distribution must be determined. Here, temperature distribution of a reactor furnace is operated by gas flow from multiple tuyeres at a furnace bottom and supplying material from the top of a furnace. The SQP method is used to control temperature distribution, too. By SQP method, two objective functions for the estimation and the control are minimized. These are stated in the following.

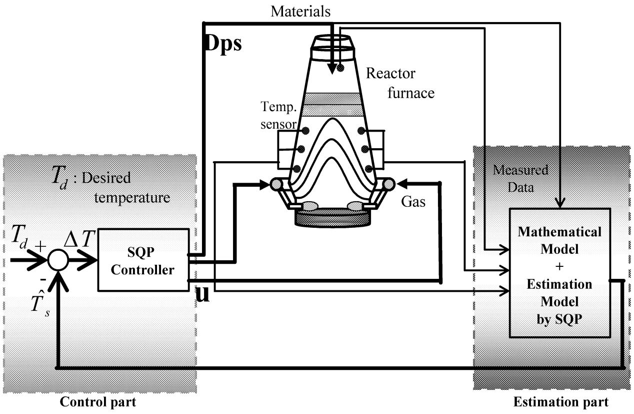


Fig. 1. Control method of temperature distribution in a reactor furnace

2.1 Criterion for Estimation of Inter Furnace Temperature Distribution

Since the central part of a reactor furnace is at high temperature and pressure, it is difficult to measure the temperature of central part in a furnace. Therefore, only the temperatures of outer side in a reactor furnace can actually be measured. In this research, inner temperature distribution of a reactor furnace is estimated by using such measured data[10]. In other words, calculated temperature distribution in a reactor furnace will conform to the measured temperature distribution when values of calculated temperature at the same positions conform to the measured data. The SQP method is applied as the way of conforming data.

Here, positions of the instrumentation are shown in Fig. 2. Instrumentations are set up along the wall of reactor furnace. Thermometers and pressure meters are set up at the inner side wall of a reactor furnace, and gas flow meters are set up at the top of a reactor furnace as shown in figure 2.

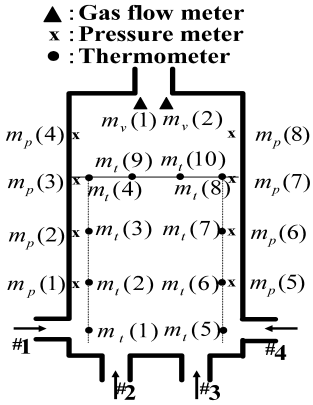


Fig. 2. Instrumentations

Here, this estimation problem is formulated in the following. Decision variables are gas volumes from inlet zones $^\sharp1$ to $^\sharp4$. When these values are decided, temperature distribution in reactor furnace can be calculated using simulator. In the estimation, the objective function is defined by equation (1), that is sum of the differences in temperature, pressure and gas flow from its instrumentations values. The value of f in equation (1) is to be minimized. In this problem, constraints are the upper and lower limit of gas volume and the equation for total quantity of gas and are written in equations (2) to (4).

$$
\begin{aligned}
f = \alpha_t \sum_{m_t} (T_s - \hat{T}_s)^2 + \alpha_p \sum_{m_p} (P - \hat{P})^2 \\
+ \alpha_v \sum_{m_v} (\mathbf{V} - \hat{\mathbf{V}})^2
\end{aligned}
\tag{1}
$$

subject to

$$c_{1h} = u_{\max} - u_h \geq 0 \tag{2}$$

$$c_{2h} = u_h - u_{\min} \geq 0 \tag{3}$$

$$c_3 = \sum_{h=1}^{4} u_h^{(l)} - C = 0 \tag{4}$$

$\hat{T}_s$: Temperatures of model, $\hat{P}$: Pressures of model,
$\hat{\mathbf{V}}$: Gas flows of model, T_s : Temperatures of furnace,
P : Pressures of furnace, $\mathbf{V}$: Gas flows of furnace
α_t, α_p, α_v : Weighting factors, u : Gas flow,
m_t : Instrumentations of temperature,
m_p : Instrumentations of pressure,
m_v : Instrumentations of gas flow,
h : Inlet zones 1~4, $u_{\max}$: Upper limit,
$u_{\min}$: Lower limit, C : Constant

2.2 Criterion for Determination of Control variables

Temperature distribution in reactor furnace can be controlled by gas volume of tuyeres at the furnace bottom and supplying materials from the furnace top[11]. In this paper, temperature control system which consists of the furnace model and the SQP method. To begin with, estimated temperature distribution in a reactor furnace at a certain time is compared with the desired temperature distribution. Then, gas volume and supplying materials size of next interval is decided to minimize the temperature differences. To know the differences, furnace simulation by applying the given gas volume is executed. Iterating the procedure, the temperature distribution at the next interval is calculated. Operating condition of a reactor furnace is determined by these iterative calculations.

Here, the control problem is formulated in the following. Decision variables are gas volumes in inlet zones $^\sharp1$ to $^\sharp4$ at the bottom of a furnace and size of supplying materials from materials entrance slot $^\sharp1$ and $^\sharp2$ at the top of a furnace. The objective function for temperature distribution control is defined by equation (5), that is sum of the squares of temperature's differences, and the maximum value of gas volume's variation. Constraints are the upper and lower limit of gas volume, the equation for total quantity of gas and the upper and lower limit of supplying materials size.

These constraints are written in equations (6) to (10).

$$f^{(l)} = w_1 \sum_{i=1}^{21} \sum_{j=1}^{12} \left(T_d(i,j) - \hat{T_s}^{(l)}(i,j) \right)^2 + w_2 \max\{|u_h^{(l+1)} - u_h^{(l)}| - a, 0\} \tag{5}$$

subject to

$$c_{1h}^{(l)} = u_{\max} - u_h^{(l)} \geq 0 \tag{6}$$

$$c_{2h}^{(l)} = u_h^{(l)} - u_{\min} \geq 0 \qquad h = 1,2,3,4 \tag{7}$$

$$c_3^{(l)} = \sum_{h=1}^{4} u_h^{(l)} - C = 0 \tag{8}$$

$$c_{4\eta}^{(l)} = Dps_{\max} - Dps_\eta^{(l)} \geq 0 \tag{9}$$

$$c_{5\eta}^{(l)} = Dps_\eta^{(l)} - Dps_{\min} \geq 0 \qquad \eta = 1,2 \tag{10}$$

T_d : Desired temperature distribution, a : Constant,
w_1, w_2 : Weighting factor, l : Time interval,
Dps : Supplying materials size,
$Dps_{\max}$: Upper limit of materials size,
$Dps_{\min}$: Lower limit of materials size,
η : Materials entrance slot

Here, values of coefficients w_1, w_2 and a are set at 10^{-4}, 100 and 1.

3 Optimization Algorithm by SQP Method

In this research, the SQP method is used for the estimation and the control of temperature distribution. The SQP method is one of the effective methods for nonlinear programming problem. In the following, optimization algorithm using the SQP method is described.

3.1 About SQP Method

Here, computing procedure of the SQP method is described.

1. Initial solution $x^{(0)}$, Hessian approximation $B^{(0)}$ and penalty parameter $r > 0$ are set up. And $k = 0$.
2. Quadratic programming problem is defined by objective function and constrained condition. When it is solved, $d^{(k)} = x^{(k+1)} - x^{(k)}$ and Lagrange multiplier $u^{(k+1)}$ are determined.

$$\nabla f(x^{(k)})^T d + \frac{1}{2} d^T B^{(k)} d \longrightarrow \min \tag{11}$$

$$c(x^{(k)}) + \nabla c(x^{(k)})^T d \geq 0 \tag{12}$$

3. Penalty parameter is updated. Here, $\sigma > 0$.

$$r = \begin{cases} \max\{|u_i^{(k+1)}| \ : i = 1,2,\cdots,m\} + \sigma, \\ \quad \text{if } r < \max\{|u_i^{(k)}| \ : i = 1,2,\cdots,m\} \\ r, \qquad \text{else} \end{cases} \tag{13}$$

4. Linear search is done, step width $t^{(k)} > 0$ is searched, and $x^{(k+1)} = x^{(k)} + t^{(k)} d^{(k)}$.
5. Hessian approximation B is updated by BFGS algorithm.

$$B^{(k+1)} = B^{(k)} + \frac{\tilde{y}^{(k)}(\tilde{y}^{(k)})^T}{(\tilde{y}^{(k)})^T s^{(k)}} - \frac{B^{(k)} s^{(k)} (s^{(k)})^T B^{(k)}}{(s^{(k)})^T B^{(k)} s^{(k)}} \tag{14}$$

$$s^{(k)} = x^{(k+1)} - x^{(k)} \tag{15}$$

$$y^{(k)} = \nabla L^{(k+1)} - \nabla L^{(k)} \tag{16}$$

$$\theta = \begin{cases} 1, & \text{if} \quad (s^{(k)})^T y^{(k)} \geq 0.2 (s^{(k)})^T B^{(k)} s^{(k)} \\ \frac{0.8 (s^{(k)})^T B^{(k)} s^{(k)}}{(s^{(k)})^T B^{(k)} s^{(k)} - (s^{(k)})^T y^{(k)}}, & \text{else} \end{cases} \tag{17}$$

$$\tilde{y}^{(k)} = \theta y^k + (1-\theta) B^{(k)} s^{(k)} \tag{18}$$

Here, $\nabla L = \nabla f - \sum_{i=1}^{M} u_i \nabla c$.

6. When convergence condition is fulfilled, this calculation is finished. Otherwise $k = k + 1$ and it returns to 2.

3.2 Estimation of Temperature Distribution by SQP Method

In actual blast furnaces, it is impossible to measure temperature in a reactor furnace except in outer side of them. Because of the above situation, we construct the estimation system using limited number of instrumentations. The method of the estimation system is shown in Fig. 3. The estimation system is constructed by the measured data in limited instrumentations.

At the beginning, the initial solution and several distributions are set up as the initial conditions. Gas volume of each tuyere is decided by the SQP method as the result of the model conforms to the measured data at the same position. When sought gas volume is applied to the model of a reactor furnace, inner furnace

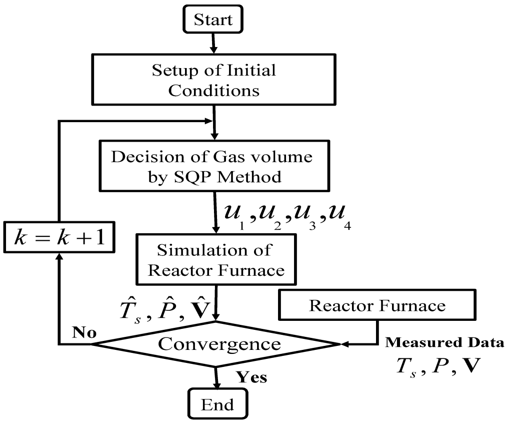


Fig. 3. Flow chart of estimation

temperature distribution is estimated. Then, the estimated value is compared with measured data. When the value of the objective function becomes to the minimum value, the iteration is finished. Otherwise, this procedure is iterated.

3.3 Decision of Operation Conditions by SQP Method

The SQP method is used to decide gas volumes. Here, the dynamic optimization algorithm to decide gas volumes by the SQP method is shown in Fig. 4.

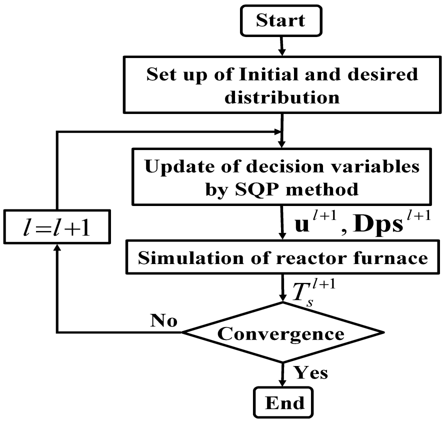


Fig. 4. Flow chart of control

To begin with, initial values of gas volume, gas flow, each temperature distributions and material charge condition are set. Then, gas volume and supplying materials size for next interval is decided by SQP method. Decided gas volume and supplying material size are applied to a reactor furnace model. This results in the change of temperature distribution in a reactor furnace and is compared with the desired temperature distribution. When the difference between calculated temperature distribution and desired one becomes smaller than ten degrees centigrade, the calculation is finished. Otherwise, time interval is updated and this procedure is iterated. Here, time interval has been taken sufficiently long time relative to a time constant of a furnace response.

4 Simulation of Temperature Distribution in Reactor Furnace

4.1 Two-dimensional Model

This paper uses Macro-Model that calculates two-dimensional macro gas flow and temperature distribution using control factors, such as gas blow and material charge as the boundary conditions of calculation. Nodes assignment for two-dimensional model is shown in Fig. 5.

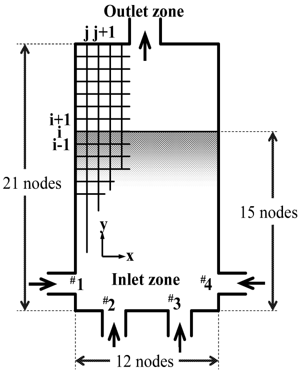


Fig. 5. Two-dimensional model

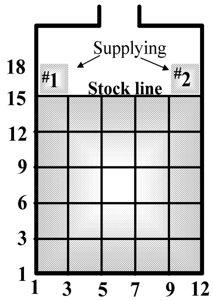


Fig. 6. Positions of supplying materials

x axis of the model is furnace width and y axis is furnace height respectively. In a blast furnace, the furnace height is about twice of the diameter. So, the number of nodes in x direction is set 12 and that in y direction is set 21 as shown in figure 5. Here, 1 node is equivalent to 2 meters. There are 4 tuyeres in the bottom of this model and high-temperature gas is discharged from it. Besides, material charge zone consist of 15 nodes as shown in Fig. 6. As shown here, materials are supplied around a reactor furnace wall.

4.2 Mathematical Models

The following is described about the mathematical equation applied to the furnace model.

4.2.1 Gas Flow Model

In gas flow, heat is conveyed with movement of fluid. In other words, when fluid flow is rapid, a lot of heat is conveyed along the direction. Since the same condition holds for the inside of reactor furnace, gas flow from tuyeres reveals much effect on the dispersion of heat. Here, the mathematical model to find the gas flow distribution is explained.

Ergun equation accompanying flow stress is adopted as the equation to find the gas flow distribution. This is described in equation (19).

$$\frac{\partial V}{\partial t} = -2\nabla p - (f_1 + f_2|V|)V + \frac{1}{Re}\Delta V \qquad (19)$$

Where, V is velocity of gas flow, p is pressure, Re is Reynolds number, f_1 and f_2 are coefficients of Ergun equation.

$$f_1 = 150\frac{(1-\epsilon)^2}{\epsilon^3}\frac{\mu}{D_p^2}, \qquad f_2 = 1.75\frac{1-\epsilon}{\epsilon^3}\frac{\rho}{D_p} \qquad (20)$$

ϵ : Fractional void volume, ρ : Density of gas
μ : Absolute viscosity of gas
D_p : Diameter of material particle

4.2.2 Temperature Model

We think of gas and solid layer to find the results of inner temperature distribution in reactor furnace. Equation to find the gas temperature distribution in reactor furnace is described by equation (21)

$$\frac{\partial T_g}{\partial t} = -(V \cdot \nabla)T_g + \lambda_g \Delta T_g - h(T_g - T_s) \qquad (21)$$

Where, T_g is gas temperature, T_s is solid temperature, λ_g is gas thermal conductivity and h is heat transfer coefficient between gas and solid. Eq. (21) is made or described based on the relation for heat conduction adding heat advection in the first term of right-hand side and the heat transfer between solid and gas in the third term of right-hand side respectively.

Equation for the solid temperature distribution in reactor furnace is described by equation (22)

$$\frac{\partial T_s}{\partial t} = \lambda_s \Delta T_s + k \cdot Q + h(T_g - T_s) \qquad (22)$$

Where, λ_s is solid thermal conductivity, Q is heat of raw material by reaction and k is reactivity coefficient. Eq. (22) is made based on equation of heat conduction, too. Moreover, Eq. (22) is additively made the heat of raw material in the second term of right-hand side and the heat transfer between solid and gas in the third term of right-hand side respectively.

4.2.3 Parameters for Equations

Generally, reaction of raw material starts with high temperature therefore reactivity coefficient k is enlarged in high temperature. However, iron ores in raw material are dissolved at about 1300 to 1400 degrees C and it is reduced to pig-iron. This reactivity coefficient k is defined by equation (23). It is associated with material size and temperature in a reactor furnace.

$$k = \frac{\alpha}{D_p} \cdot \exp\left(-\frac{E}{R \cdot T_g}\right) \cdot \beta V k' \qquad (23)$$

$$k' = \frac{1}{1 + \exp\{(T_g - 1700)/\gamma\}} \qquad (24)$$

R : Gas constant, E : Activity energy
α, β, γ : constant

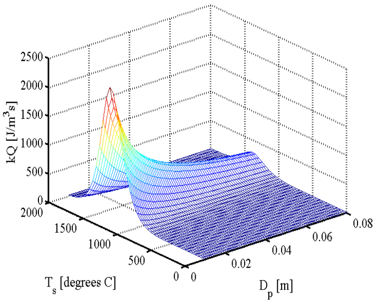


Fig. 7. Calorific value per unit product of the material particle

4.3 Solution Procedure for Simulation

Temperature distribution in reactor furnace is calculated by solving gas flow equation, gas temperature

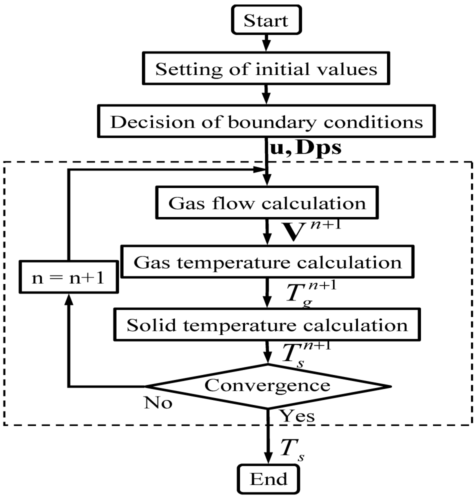


Fig. 8. Flow chart of simulation

Table. 1. Measured data of instrumentations

	1	2	3	4	5	6	7	8	9	10
$T(m_t)$	1189	1028	992	840	1391	1080	1003	845	1382	1383
$P(m_p)$	0.17	0.16	0.14	0.13	0.18	0.16	0.14	0.13	-	-
$V(m_v)$	(0.13,0.42)	(-0.13,0.42)	-	-	-	-	-	-	-	-

equation and solid temperature equation. In this paper, finite-difference approximation method is used to calculate the gas flow and the temperature distribution. Flow chart of the calculation is shown in Fig. 8.

When input values such as gas volume of each tuyeres and supplying material size are given, temperature distribution in a reactor furnace is calculated. These calculations are continued until the convergence condition is fulfilled. The convergence condition is described in equation (25).

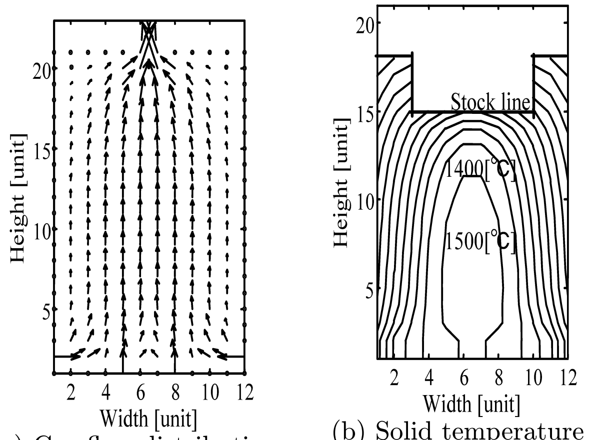
$$\max_{i,j} |T_s^{n+1}(i,j) - T_s^n(i,j)| < \sigma \quad \text{and} \quad n \geq \tau \tag{25}$$

Here, σ and τ are set at 0.5 and 100 respectively.

4.4 Numerical Simulation of Gas flow and Temperature

Temperature distribution in a reactor furnace is calculated by the method stated above. Gas volume of all tuyeres is set at 2 units and gas temperature is set at 1200 degrees centigrade and supplying material size is 0.045 meters in diameter.

In the following, simulation results are shown. In Fig. 9(a), the gas volume distribution is shown and in Fig. 9(b), the solid temperature distribution is shown. The gas flows from tuyeres at the bottom to a discharge equipment of the top. The solid temperature is high at center of a reactor furnace, and is gradually decreased toward the furnace wall.



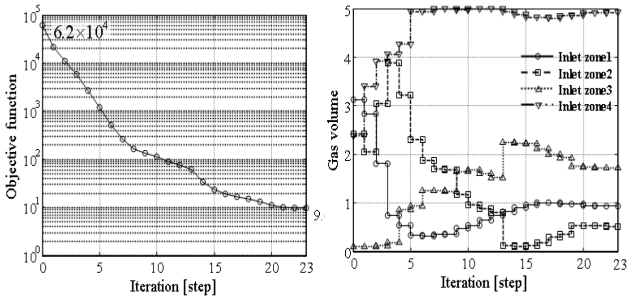
(a) Gas flow distribution (b) Solid temperature distribution

Fig. 9. Results of furnace simulation

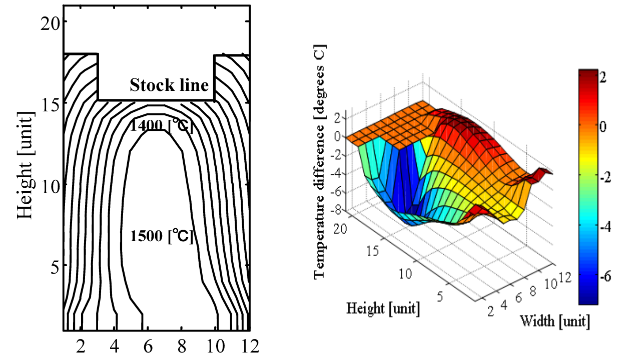
5 Numerical Experiment of SQP Application

5.1 Estimation of Temperature Distribution

Estimation of temperature distribution in a reactor furnace is calculated by the method shown in Fig. 3 of section 3.2. Measured data of actual furnace for numerical experiment are shown in Table 1. These data



(a) Transition of objective function (b) Transition of decision variables



(c) Estimated temperature distribution (d) Temperature difference

Fig. 10. Results of estimation

are measured at nodes shown in Fig. 2. Temperatures, pressures and gas flows are measured at ten, eight and two points around a furnace. Here, gas flow is given by vector value. Using the data temperature distribution in a reactor furnace is estimated.

In the following, simulation results are shown. Fig. 10(a) shows the transition of objective function and Fig. 10(b) shows the transitions of gas blow which are the control variables. In Fig. 10(c), estimated temperature distribution is shown. Temperature difference of estimated one and desired one is shown in Fig. 10(d).

As shown here, the value of the objective function decreases with iterations. After 23 times iterations, it converges at 9.6. When the transition of gas flow is seen, gas volume from tuyere ♯4 becomes larger than others. Herewith, estimated temperature distribution is high in right of a center of a furnace. As for the difference of the estimated and the measured temperature, estimated one is equated to measured one at almost all nodes. The maximum difference is 7.2 degrees centigrade at the center of a reactor furnace. Temperature differences of left side become larger than right side. Near the position of instrumentations, temperature difference is small and as it is pulled away from instrumentations, temperature difference becomes large.

5.2 Control of Temperature Distribution

Control of temperature distribution in a reactor furnace is calculated by the method shown in Fig. 4. The initial temperature distribution and the desired temperature distribution are shown in Fig. 11 and Fig. 12 respectively.

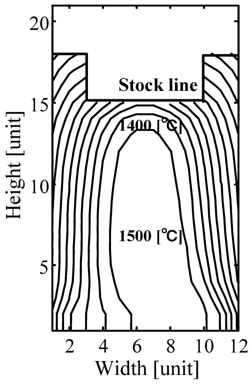


Fig. 11. Initial temperature distribution

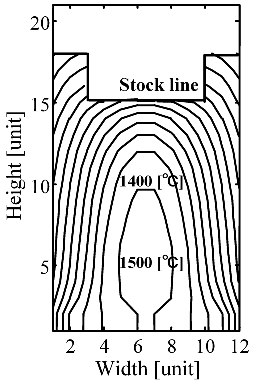
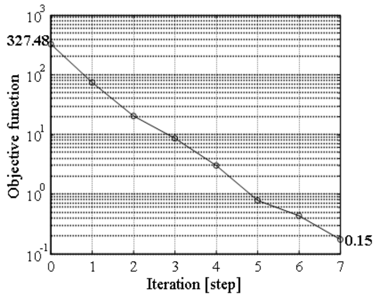
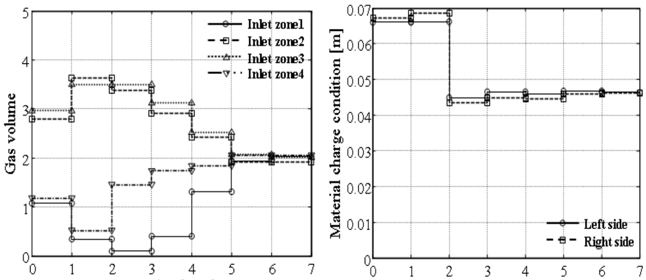


Fig. 12. Desired temperature distribution

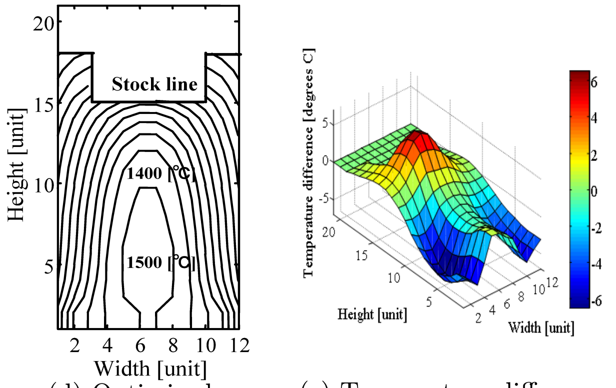


(a) Transition of objective function



(b) Transition of gas flow

(c) Transition of supplying material size



(d) Optimized temperature distribution

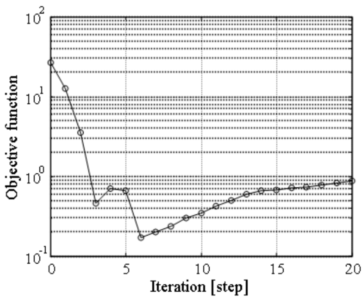
(e) Temperature difference

Fig. 13. Results of control

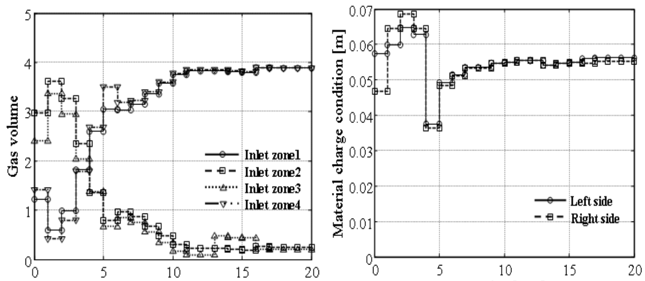
Temperature distribution in a reactor furnace is controlled so as to attain the desired temperature distribution by changing supply value the operation of gas volumes from each tuyeres and materials from top of a furnace.

In the following, simulation results are shown. The transition of the objective function, the transitions of gas blow which is control variables and the transitions of supplying material size which is control variables are shown in Fig. 13(a), Fig. 13(b) and Fig. 13(c) respectively. In Fig. 13(d), optimized temperature distribution is shown. In Fig. 13(e), temperature difference between the desired and the optimized temperature distribution is shown.

As for the transition of gas flow from tuyeres, gas volumes from tuyere ♯1 and ♯4 decrease slightly and

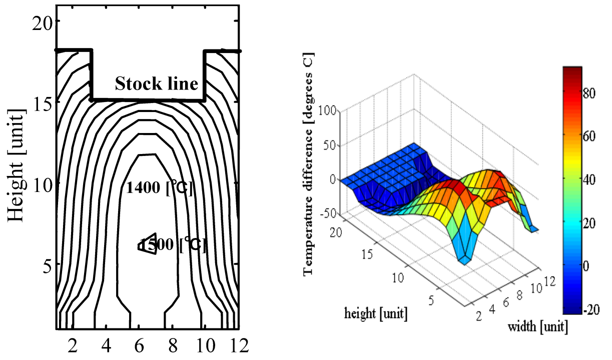


(a) Transition of objective function



(b) Transition of gas flow

(c) Transition of supplying material size



(d) Optimized temperature distribution

(e) Temperature difference

Fig. 14. Results of control without estimation

them from tuyere $^\sharp$2 and $^\sharp$3 increase slightly in early time. Then, gas volumes from tuyere $^\sharp$1 and $^\sharp$4 increase slightly and them from tuyere $^\sharp$2 and $^\sharp$3 decrease slightly. When gas volume from tuyere $^\sharp$1 and them from tuyere $^\sharp$4 are compared, gas volume from tuyere $^\sharp$4 become more than it from tuyere $^\sharp$1. Finally, gas volumes of all tuyeres become about 2 units. When the transition of supplying material size is seen, both sides of material size become large in early time. As time passes, material size reduces from 0.067 meters to 0.047 meters at both sides. The objective function decreases at every iterations. Temperature difference between the desired and the optimized temperature distribution is 6.5 degrees centigrade at the maximum.

Furthermore, result to have been controlled not temperatures of all nodes to be obtained by estimated temperature distribution in a reactor furnace but measured temperatures are shown at the following. This objective function is described at equation (26). The change of equation (26) from equation (5) is the number of positions evaluated temperature.

$$f^{(l)} = w_1 \sum_{m_t} \left(T_d(i,j) - \hat{T}_s^{(l)}(i,j) \right)^2 + w_2 \max\{|u_h^{(l+1)} - u_h^{(l)}| - a, 0\} \qquad (26)$$

In the following, simulation results are shown. Simulation conditions are the same as the above. The transition of objective function, the transitions of gas blow which is control variables and the transitions of supplying material size which is control variables are shown in Fig. 14(a), Fig. 14(b) and Fig. 14(c) respectively. In Fig. 14(d), optimized temperature distribution is shown. In Fig. 14(e), temperature difference between the desired and the optimized temperature distribution is shown.

As in Fig. 14(a) the calculation was not able to fulfill convergence conditions until 20 times iterations. Seeing from figures 11 and 12, Temperature in a reactor furnace is higher than the desired temperature in the early stages. As in Fig. 14(b), gas volume from tuyere $^\sharp$1 and $^\sharp$4 set at near instrumentation points is reduced so as to decrease furnace heat. As shown in Fig. 14(c), supplying material size becomes large for the same purpose. After three iterations, temperature difference decreases. However, because of the large time delay in heat transfer phenomenon, the inner temperature decreases too much. Then, gas volume from tuyere $^\sharp$1 and $^\sharp$4 rises and supplying material size becomes small in order to raise the furnace heat. In the process, gas volume from tuyere $^\sharp$2 and $^\sharp$3 is decreasing and temperature of the central part of a reactor furnace becomes smaller than the desired temperature. Therefore, as shown in Fig. 14(e), the value of temperature difference is the largest at the central part and is 91.4 degrees centigrade. Further, as shown in Fig. 14(d), the temperature in the central part of a furnace differs from its desired value.

As the results, it is verified that the estimation of temperature distribution is needed in order to control the temperature distribution in wide area of a reactor furnace.

6 Production of Pig-Iron

As described above, control of temperature distribution in the reactor furnace was studied. In this section, we will proceed to study the control of the production of pig-iron. Therefore, it is attempted to enforce the reactor furnace model in order to describe the production of pig-iron and solid flow distribution adding to the existing reactor furnace model.

6.1 About Amount of Production

The schematic illustration of a blast furnace is shown in Fig. 15. Ores and Cokes are put from the top of the furnace into the furnace. Then, ores are transformed into pig-iron in the reactor furnace and pig-iron drops at the bottom of the reactor furnace. Finally, accumulated pig-iron is flowed out from tap hole. As described above, in reactor furnace, the condition of the upper part is a solid and the condition of the lower part is a liquid. Boundary between a solid and a liquid is cohesive zone.

Here, the production of pig-iron is defined as the amount of a liquid transformed from a solid. Therefore, it is found that solid flow distribution in cohesive zone is related to the production of pig-iron. Temperature of the cohesive zone is set 1340 degrees centigrade. Consequently, solid flow of places of 1340 degrees centigrade is defined as the production of pig-iron shown in Fig. 16. The equation for the production of pig-iron is described in equation (27).

$$W = \int_{t_1}^{t_2} \int_{\Delta x}^{N\Delta x} V_s(x)dxdt \tag{27}$$

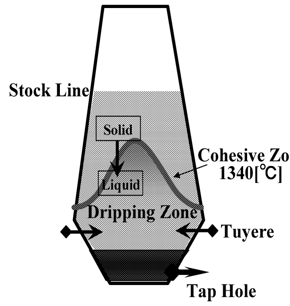


Fig. 15. Schematic illustration of reactor furnace

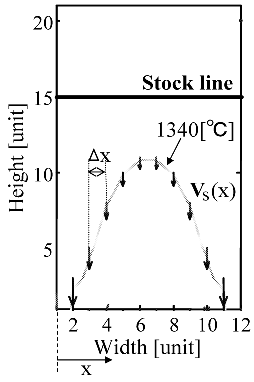


Fig. 16. Production of pig-iron

6.2 Mathematical Model for Solid Flow

6.2.1 Solid Flow Model

The equation of solid flow is described in equation (28).

$$\nabla(\rho_s V_s) = R_s \tag{28}$$

Where, ρ_s, V_s and R_s are the density of raw materials, the velocity and drifted amount.

Because solid flow is piston flow, flux line of solid flow is shown in Fig. 17. Therefore, the radial distribution of the velocity is described in equation (29).

$$y = a_0 + a_1x + a_2x^2 + a_3x^3 \tag{29}$$

Where, x is a radius of nondimensional parameter and values of a_0 to a_3 are constants.

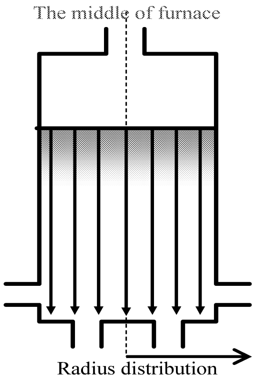


Fig. 17. flux line of solid flow

6.2.2 Solid Temperature Model

Solid flow affects solid temperature distribution. Therefore, the equation for solid temperature distribution is to change into equation (30). A changed point between equation (30) and equation (22) is to add heat advection in the first term of right-hand side.

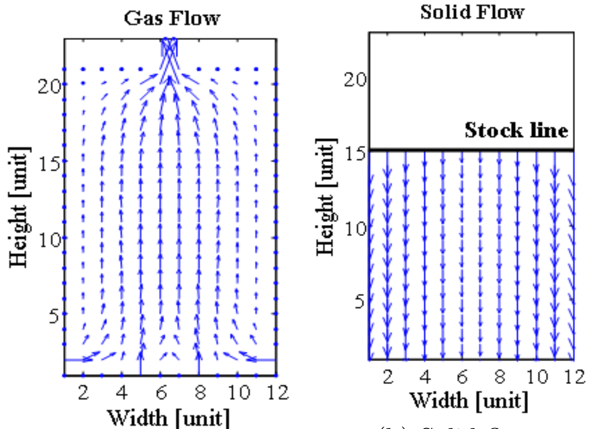
$$\frac{\partial T_s}{\partial t} = -(V_s \cdot \nabla)T_s + \lambda_s \Delta T_s + k \cdot Q + h(T_g - T_s) \tag{30}$$

6.3 Numerical Simulation

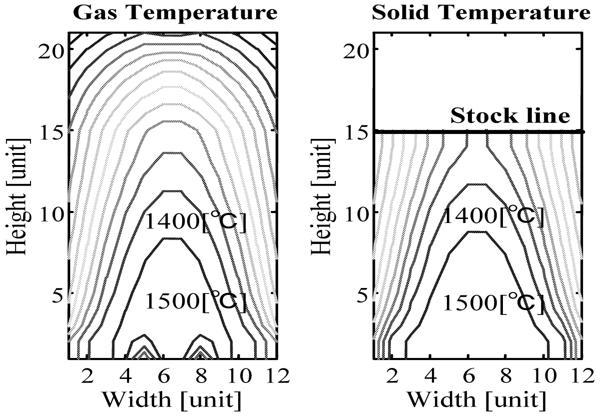
Each distribution in a reactor furnace is calculated by the flow chart shown in figure (8). Gas volume of all tuyeres is set at 2 units, gas temperature is set at 1200 degrees centigrade, supplying material size is 0.045 meters in diameter and the height of stockline is 15 nodes.

In the following, simulation results are shown. In Fig. 18(a), the gas flow distribution is shown and in Fig. 18(b), the solid flow distribution is shown. In Fig. 18(c), the gas temperature distribution is shown and in Fig. 18(d), the solid temperature distribution is shown. The pressure distribution is shown in Fig. 18(e).

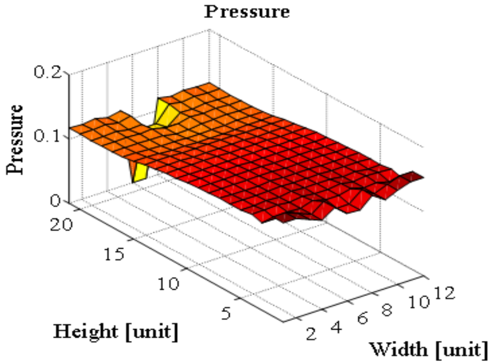
As shown in figure 9(b), the solid flow around the furnace is faster than the flow of the central part. As shown in figure 9(b) and figure 18(d), the hot part of solid temperature distribution calculated by reactor furnace model added solid flow is widened at the bottom of furnace.



(a) Gas flow distribution (b) Solid flow distribution



(c) Gas temperature distribution (d) Solid temperature distribution



(e) Pressure distribution

Fig. 18. Results of model with solid flow

6.4 Simulation of Pig-Iron Production

The production of pig-iron described in equation (27) is examined by reactor furnace model adding solid flow distribution. The production of pig-iron is related to gas volume and stockline level. Therefore, when the values of gas volume and stockline level are varied, the change in the production of pig-iron is examined.

The simulation results are shown in the following. In Fig. 19, the change in the production of pig-iron by gas volume is shown. And, in Fig. 20, the change in the production of pig-iron by stockline level is shown.

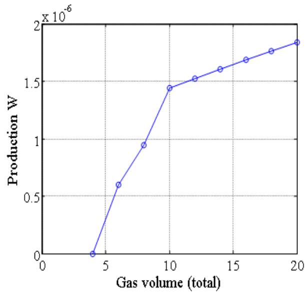


Fig. 19. Production change by gas volume

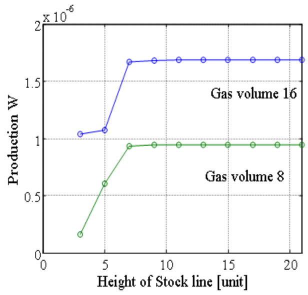


Fig. 20. Production change by stockline level

As shown in figure 19, the production of pig-iron elevates when gas volume is increased. When the volume of gas volume is less than 10, increasing rate of the production of pig-iron is becomes large. When the volume of gas volume is greater than 10, increasing rate of the production of pig-iron is declined. As shown in figure 20, the production of pig-iron elevates when stockline level ascends. However, when the volume of stockline is greater than 7, the production of pig-iron is nearly constant.

In future works, control of the production of pig-iron by gas volume and stockline level will be studied.

7 Conclusion

In this paper, estimating method of the inner furnace temperature distribution and control method of gas blowing from multiple tuyeres and supplying material to achieve the desired temperature distribution are proposed. For these purposes, a SQP method which is an effective method in solving nonlinear optimization problem is used both to estimate the temperature distribution in a reactor furnace and to determine the control variables. It is checked through numerical experiment that even if there are some lacks in measured data, temperature distribution in a furnace could be estimated. Further, control variables such as gas volume and supplying material for achieving desired temperature distribution are determined. As a future assignment, time-optimal control of temperature distribution in a reactor furnace will be raised. The consideration of the time when the temperature distribution in a reactor furnace was conformed to a desired temperature distribution is left for the future study.

Moreover, the production of pig-iron will be controlled by gas volume and stockline level. The operating cost will be defined by mathematical model and the planning system optimized considering both the production of pig-iron and the operating cost will be constructed.

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