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Control Method for Temperature Distribution in Reactor Furnace by Sequential Quadratic Programming Method

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Temperature distribution in the reactor furnace is mainly operated by gas blowing from multiple tuyeres and material charge distribution. The objective of our research is obtain the optimal profile of gas flow to control temperature distribution in the reactor furnace in the shortest possible time. We formulated the optimization problem to reduce deviation of temperature distribution from its desired one in the reactor furnace. Based on the formulation, gas blow conditions are optimized by a sequential quadratic programming method to realize the desired temperature distribution. The validity of the method was checked through numerical experiments.

1 Introduction

Reactor furnaces such as a blast furnace are playing vital roles in the industrial systems. However, phenomena inside of the furnace is complex and operation of reactor furnace is a form that still depends on experience and intuition of skilled operators.

Since various changing factors, such as a flow of gas, a chemical reaction, burn-through and anastomoses of iron ore and movement of a filling, are entangled intricately, the inside of reactor furnace has been a black box till now.

Meanwhile, stable furnace operations and low cost operation are expected in the actual work front. Moreover, automated operations are needed as decrementation of skilled operators and difficulty in finding successors.

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 blowing in multiple tuyeres as boundary conditions.

First, the simulator for gas flow and temperature distribution in the furnace was developed, which used control factors as boundary conditions. This simulator is made of simplified model that enables consideration of heat transfer phenomena in reactor furnace.

And a sequential quadratic programming method is used to control temperature distribution in a reactor furnace. In this research, the control system which is adapted the sequential quadratic programming method and reactor furnace model was constructed. Temperature distribution in a reactor furnace was iteratively

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calculated by this model. In the iteration, gas volume of next iteration was decided by the sequential quadratic programming method. Temperature distribution in a reactor furnace was controlled by means of these iterated calculations.

On one hand, there is a issue when it is difficult to measure temperatures wholewhere in a reactor furnace. Because of the above situation, we examined about the control system limiting the number of instrumentations for measuring temperature.

2 Reactor Furnace Model

In the following, the reactor furnace model will be constructed assuming a blast furnace in steel works. Besides, brief description of phenomena in the blast furnace and the construction of mathematical description will be stated.

2.1 Temperature Distribution in Blast Furnace

When pig-iron is made from the iron ore, the furnace called blast furnace is used. Diagrammic illustration of blast furnace is shown in Fig. 1.

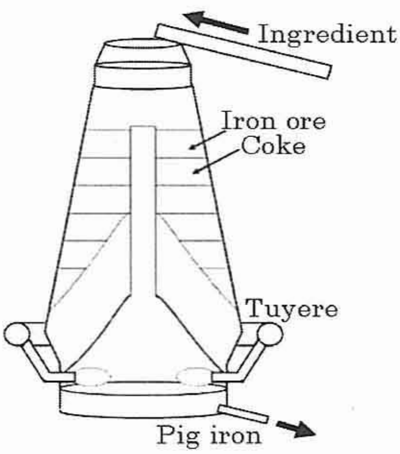


Fig. 1: Diagrammic Illustration of Blast Furnace

The height of blast furnace is about 40 meters and the diameter of it is about 20 meters. Moreover, iron ores and Cokes are charged by turns in it. Because blasts of hot air of about 1200 degrees (C) are blown from tuyeres equipped along the side of a blast furnace bottom, cokes burns and carbon monoxide is generated. Iron ores is reduced in about 8 hours by the reaction with this carbon monoxide and pig-irom accumulates in a blast furnace bottom. On the other hand, blasts of hot air blown from tuyeres is discharged from the blast furnace upper part.

2.2 Mathematical Models [1][2]

2.2.1 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 (1) [3].

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

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

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

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

2.2.2 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 (3)

$$\frac{\partial T_g}{\partial t} = -(V\cdot\nabla)T_g + \lambda_g\Delta T_g - h(T_g - T_s) \tag{3}$$

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. (3) 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 (4)

$$\frac{\partial T_s}{\partial t} = \lambda_s\Delta T_s + k\cdot Q + h(T_g - T_s) \tag{4}$$

Where, λ_s is solid thermal conductivity, Q is heat of raw material by reaction and k is reactivity coefficient. Eq. (4) is made based on equation of heat conduction, too. Moreover, Eq. (4) 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.

2.2.3 Parameters for Equations

In reactor furnace, raw materials are filled to the height of two-thirds of furnace's height. The central part of reactor furnace is filled with fine-grained materials to eased the reaction. And outside part of reactor furnace is filled with grainy materials. Material charge condition is shown in Fig. 2.

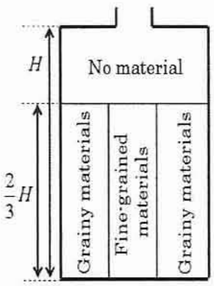


Fig. 2: Material Charge Condition

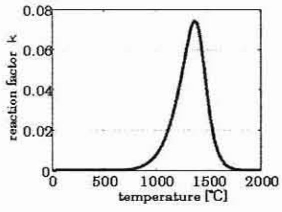
Generally, reaction of raw material starts with high temperature therefore reactivity coefficient k is enlarged in high temperature. However, iron ores in raw material are dissolved at about 1300 to 1400 degrees (C) and it is reduced to pig-iron. This reactivity coefficient k fine-grained and grainy materials will be decreased after reduction and its characteristics are shown in Fig. 3, Fig. 4 respectively [4][5][6].

$$k = \frac{\alpha}{D_p} \cdot \exp\left(-\frac{E}{R \cdot T_g}\right) \cdot \beta V k' \quad (5)$$

$$k' = \frac{1}{1 + \exp\{(T_g - 1700)/\gamma\}} \quad (6)$$

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

Fig. 3 shows the characteristics for reactivity coefficient of fine-grained materials. On the other hand, Fig. 4 shows reactivity coefficient of grainy materials.



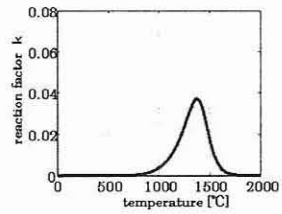


Fig. 3: reactivity coefficient of fine-grained materials

Fig. 4: reactivity coefficient of grainy materials

3 Numerical Simulation of Temperature Distribution

3.1 Two-dimensional Model [7]

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.

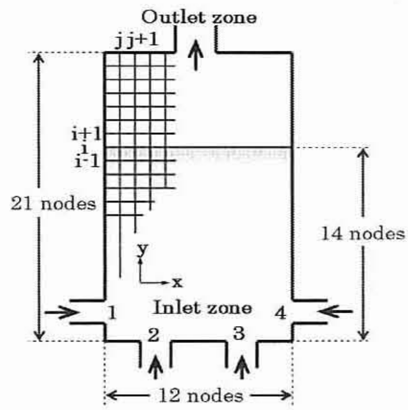


Fig. 5: Two-dimensional Model

x axis of the model is width direction and y axis is height direction respectively. In a real furnace, since the height is twice of the diameter, x direction has 12 nodes and y direction has 21 nodes. Moreover, material charge nodes consist of 14 nodes. There are 4 tuyeres in the bottom of this model and a discharge equipment of gas flow in the top of portion.

3.2 Solution Procedure for Simulation

Temperature distribution in reactor furnace is calculated by solving gas flow equation, gas temperature equation and solid temperature equation simultaneously. In this paper, finite-difference approximation method is used to calculate of gas flow and temperature distribution. Flow chart of the calculation is shown in Fig. 6.

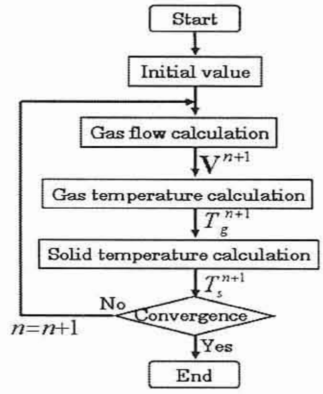


Fig. 6: Flow Chart of Calculation

The calculation is started using control factors, volume of gas flow, temperature of gas flow, material distribution in furnace, as initial conditions or boundary conditions. The gas flow calculation is solved by MAC method [8]. Gas flow and pressure distribution are found by the gas flow calculation. Next, gas temperature distribution is found by the gas temperature calculation and solid temperature distribution is found by the solid temperature calculation. These calculations are continued until the convergence condition is fulfilled. The convergence condition is described in equation (7). As shown here, when the difference of temperature between adjacent iterations becomes less than the time interval of iterations, the convergence is considered to be attained.

$$\max_{i,j} |T_g^{n+1}(i,j) - T_g^n(i,j)| < \Delta t \qquad (7)$$

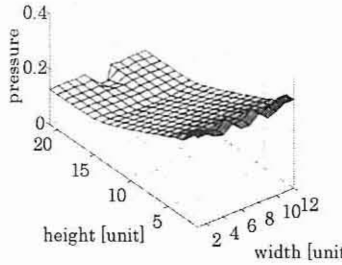


Fig. 7: Pressure Distribution

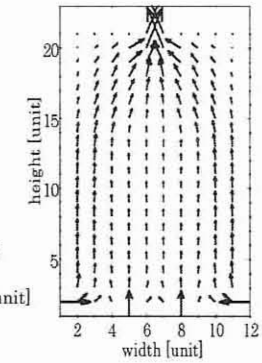


Fig. 8: Gas Flow Distribution

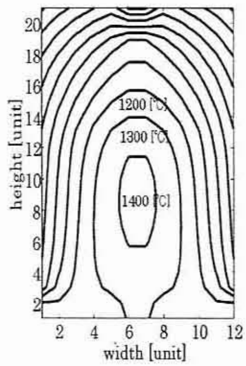


Fig. 9: Gas Temperature Distribution

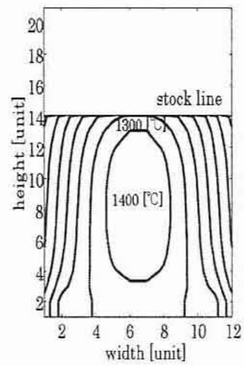


Fig. 10: Solid Temperature Distribution

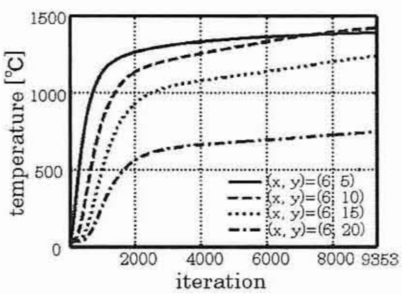


Fig. 11: Time Characteristics of Gas Temperature

3.3 Numerical Simulation

Temperature distribution in 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 (C).

In the following, simulation results are shown. In Fig. 7, the pressure distribution is shown, and in Fig. 8, the gas volume distribution is shown. In Fig. 9, the gas temperature distribution is shown and in Fig. 10, the solid temperature distribution is shown.

The gas pressure decreases at the height where raw materials are charged. And it is constant at the vacant area without charged materials. The gas flows from tuyeres in the bottom to a discharge equipment in the top. The gas temperature is high in the center of reactor furnace, and is gradually decreased in the direction to furnace wall. The solid temperature state is closely similar to the gas temperature. However, the solid temperature is slightly higher than that of the gas. Further, time characteristics of the gas temperature is shown in Fig. 11. In early time, gas temperature increases rapidly. Subsequently, it increases gradually. Finally, it becomes static state.

4 Control of Temperature Distribution [9]

Temperature distribution in reactor furnace is controlled by gas volume of tuyeres. In this paper, temperature control system consists of furnace model and sequential quadratic programming method. The structure of the control system is shown in Fig. 12.

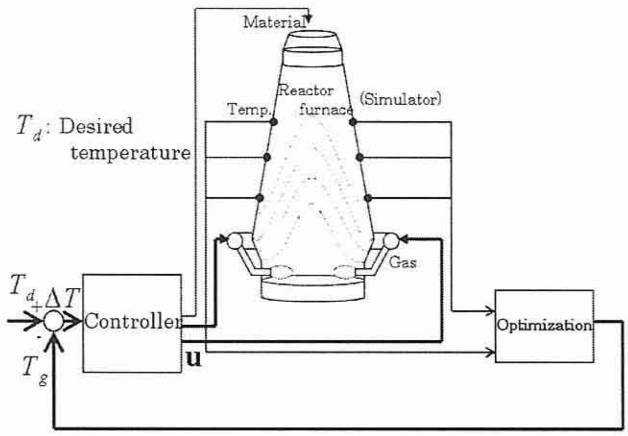


Fig. 12: Control System for Temperature Distribution

To begin with, temperature distribution in reactor furnace at a certain time is compared with the desired temperature distribution. Then, gas volume of next interval is decided by the temperature differences. Further, the reactor furnace simulation by applied gas volume is executed, and temperature distribution of next interval is calculated. Temperature distribution in reactor furnace is modified by these iterative calculations.

4.1 Control Method

Here, the problem matching temperature distribution in reactor furnace to desired temperature distribution is formulated as an optimization problem.

Decision variables are gas volumes in inlet zones ♯1 to ♯4. Since the reactor furnace is operated for many hours, gas volume is changed for some duration of plural iterations. Since the purpose of this research is to match temperature distribution in reactor furnace to that of desired temperature distribution, the objective function is defined by equation (8). Eq. 8 is the sum of square value of temperature difference in all nodes and the constraints for gas volume variations. In this problem, constraints are the upper and lower limit of gas volumes. Constraints are defined by equation (9).

$$f^l = a_1 \sum_{i=1}^{21} \sum_{j=1}^{12} \left(T_d(i,j) - T_g^l(i,j)\right)^2 + a_2 \max\{|u_h^{l+1} - u_h^l| - a_3, 0\} \quad (8)$$

subject to

$$c_{1h}^l(u) = u_{\max} - u_h^l \geq 0$$
$$c_{2h}^l(u) = u_h^l - u_{\min} \geq 0 \quad (9)$$

T_d : Desired temperature distribution,
u : Decision variables, h : Inlet zones 1∼4
$u_{\max}$: Upper limit, l : Interval
$u_{\min}$: Lower limit, a_1, a_2, a_3 : Constant

Here, value of coefficient a_1 is set at 10^{-4}.

4.2 Control Algorithm

The sequential quadratic programming (SQP) method is used to decide gas volumes. SQP method is one of the effective methods for nonlinear programing problem. The dynamic optimization algorithm for temperature distribution in reactor furnace by SQP method is shown in Fig. 13.

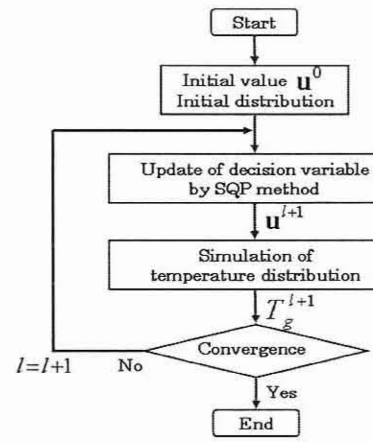


Fig. 13: Flow chart of control

To begin with, initial values of gas volume, gas flow, each temperature distributions and material charge condition are set. Then gas volume for next interval is decided by SQP method. Decided gas volume is operated to the reactor furnace to estimate temperature distribution in reactor furnace. Estimated result compared with desired temperature distribution. When the difference between them becomes smaller than one percent, the calculation is finished. Till the convergence condition is fulfilled, this procedure is iterated.

4.3 Numerical Experiment

Control of temperature distribution in reactor furnace is calculated by the method shown in Fig. 13. Initial temperature distribution is shown in Fig. 14, and desired temperature distribution is shown in Fig. 15.

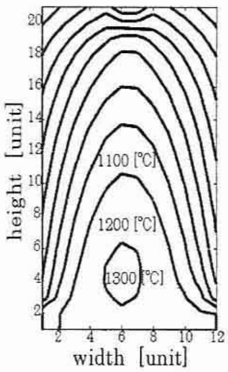


Fig. 14: Initial Temperature Distribution

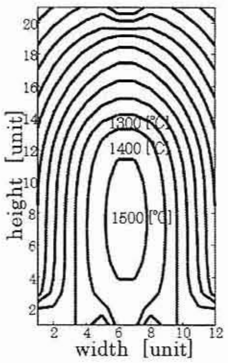


Fig. 15: Desired Temperature Distribution

Temperature distribution in reactor furnace is controlled to attain the desired temperature distribution by adding the operation of gas volumes of each tuyeres to initial temperature distribution.

In the following, simulation results are shown. In Fig. 16, the transitions of control variables are shown and in Fig. 17, the transition of objective function is shown. In Fig. 18, Optimized temperature distribution is shown. In Fig. 19, temperature distribution between desired and optimized temperature distribution is shown.

When the transition of decision variables is seen, gases of enormous volume are blown from all tuyeres in early time. Then, tuyere 1 and 4 decrease slightly and tuyere 2 and 3 decrease sharply. Finally, gas volumes of all tuyeres become about 2 units. The objective function decreases at every iterations. When gases blow as shown in Fig. 16, temperature distribution in the reactor furnace gets close to desired temperature distribution. Temperature difference between desired and optimized temperature distribution is 12 degree (C) at the maximum.

Next, it is considered how lomg it takes time to the achievement of desired temperature distribution. When gas volumes are kept a constant, number of iterations is shown in Fig. 20.

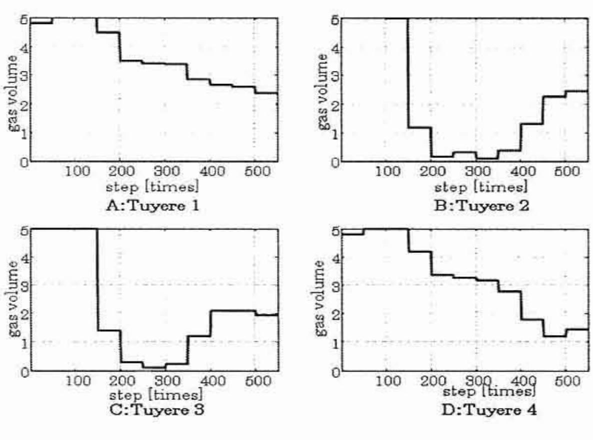


Fig. 16: Transition of Decision Variables

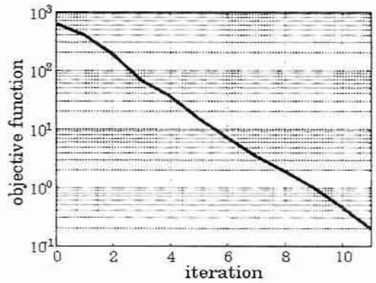


Fig. 17: Transition of Objective Function

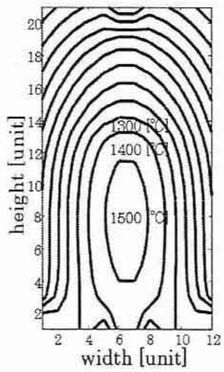


Fig. 18: Optimized Temperature Distribution

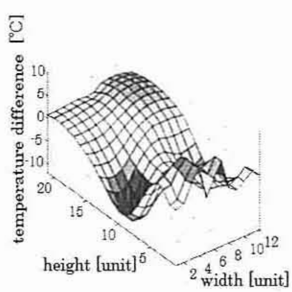


Fig. 19: Temperature Difference

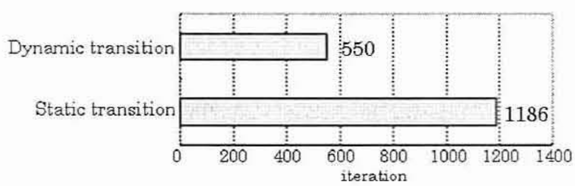


Fig. 20: Calculated Iteration

Number of iterations to the achievement of desired temperature distribution is reduced to 50 percents by dynamic operation.

5 Arrangement of Instrumentation

In actual blast furnace, it is impossible to measure temperature everywhere in reactor furnace except outer side of it. Since the central part of reactor furnace is at high temperature and pressure, it is difficult to measure temperature in the center, and only temperatures of outer side of reactor furnace can be actually measured. Because of the above situation, the problem is the construction of the control system using limited number of instrumentations. The structure of control system is shown in Fig. 21.

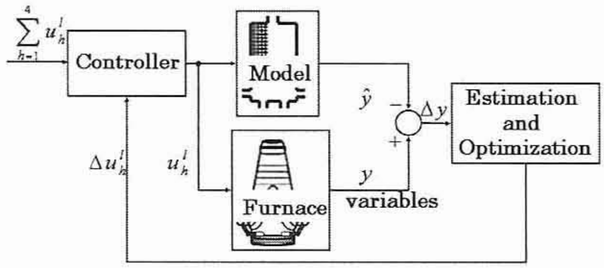


Fig. 21: Control System of Reactor Furnace

This control system is usable for the actual reactor furnace. Total blowing gas volume is set to constant, and outputs of reactor furnace are temperature, pressure and gas flow observable only by limited instrumentation points. Temperature distribution in reactor furnace is to be estimated and optimized from these limited data. The sequential quadratic programming method is used in the control system in the same way as used in chapter 4.

5.1 Design of Instrumentation

Instrumentations are set up along the outside of reactor furnace. These are shown in Fig. 22. Thermometers and pressure meters are set up at the inner side wall of reactor furnace, and gas flow meters are set up at the top of reactor furnace.

Measured values in reactor furnace are compared with corresponding values by the simulation. Since temperature of all nodes is known in simulation, temperature distribution in reactor furnace is estimated by knowing differences of these values. And then, gas volume of tuyeres can be determined.

Here, this problem is formulated in the following.

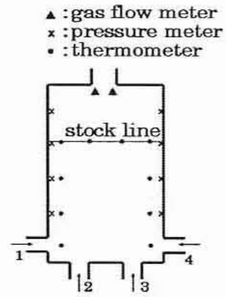


Fig. 22: Instrumentations

Decision variables are gas volumes in inlet zones ♯1 to ♯4. When these values are decided, temperature distribution in reactor furnace can be solved. Objective function is defined by equation (10), and differences of temperature, pressure and gas flow from instrumentations values are reduced. In this problem, constraints are the upper and lower limit of gas volume and the equation for total quantity of gas. These constraints are written by equation (11).

$$f^l = \alpha_t \sum_{m_t} (Td - Tg)^2 + \alpha_p \sum_{m_p} (Pd - P)^2 + \alpha_v \sum_{m_v} (Vd - V)^2 \quad (10)$$

subject to

$$\begin{aligned} c^l_{1h}(u) &= u_{\max} - u^l_h \geq 0 \\ c^l_{2h}(u) &= u^l_h - u_{\min} \geq 0 \\ c^l_{3h}(u) &= u^l_1 + u^l_2 + u^l_3 + u^l_4 = C \end{aligned} \quad (11)$$

Td : Temperatures of model, Pd : Pressures of model
Tg : Temperatures of furnace, P : Pressures of furnace
Vd : Gas flows of model, V : Gas flows of furnace
α_t, α_t, α_t : Weighting factors
m_t : Instrumentations of temperature
m_p : Instrumentations of pressure
m_v : Instrumentations of gas flow
u : Decision variables, h : Inlet zones 1∼4
$u_{\max}$: Upper limit, l : Interval
$u_{\min}$: Lower limit, C : Constant

5.2 Numerical Experiment

Control of temperature distribution in reactor furnace is calculated by the method shown in Fig. 21. Initial temperature distribution in reactor furnace is shown in Fig. 23, initial gas flow distribution is shown in Fig. 24 and initial pressure temperature is shown in Fig. 25.

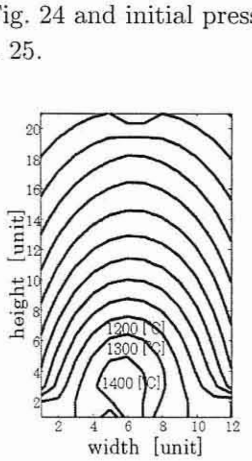


Fig. 23: Initial Temperature Distribution

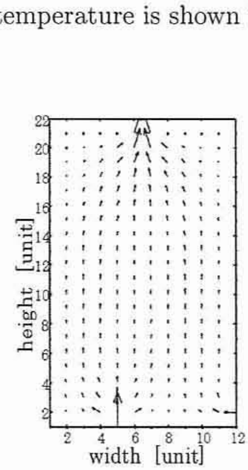


Fig. 24: Initial Gas Flow Distribution

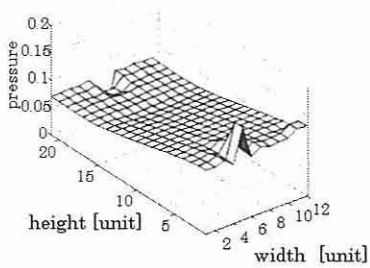


Fig. 25: Initial Pressure Distribution

In the following, simulation results are shown. In Fig. 26, the transition of decision variables is shown and in Fig. 27, the transition of objective function is shown. In Fig. 28, optimized temperature distribution is shown and in Fig. 29, optimized gas flow distribution is shown. In Fig. 30, optimized pressure distribution is shown.

When the transition of decision variables is seen, gas volume of tuyere 1 and 3 are small and tuyere 2 and 4 are large in early iteration. Then, gas volume of tuyere 2 decreases slightly and gas volume of tuyere 3 rises gradually. Finally, gas volumes of all tuyeres become about 2 units. And total gas volume is kept a constant. The objective function decreases at every iterations. When gases blow as shown in Fig. 26, temperature, gas flow and pressure distribution in the reactor furnace are estimated.

When temperature distribution in reactor furnace is measured in all nodes, the estimated temperature distribution is compared with it. The error between actual and estimated temperature distribution is shown in Fig. 31.

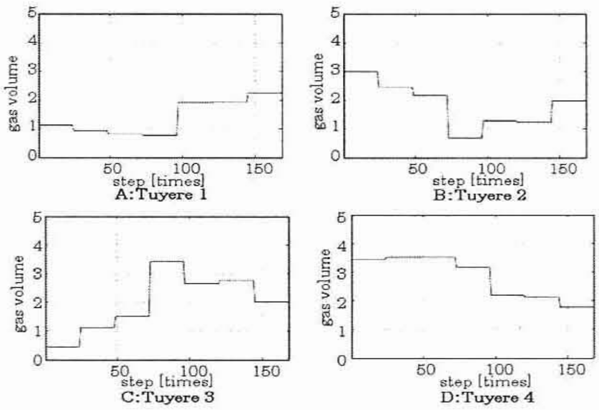


Fig. 26: Transition of Decision Variables

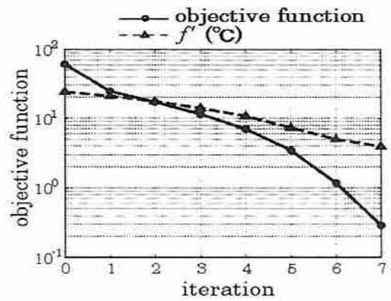


Fig. 27: Transition of Objective Function

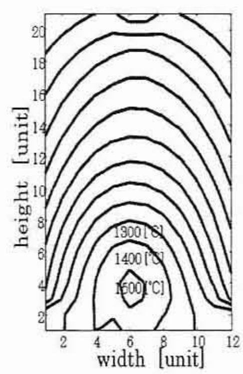


Fig. 28: Optimized Temperature Distribution

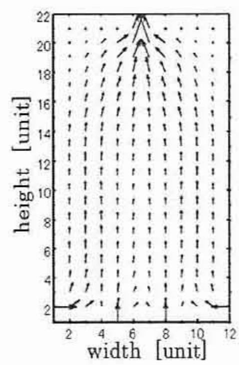


Fig. 29: Optimized Gas Flow Distribution

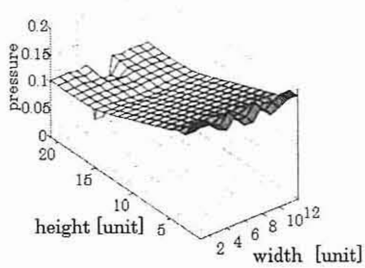


Fig. 30: Optimized Pressure Distribution

Table. 1: Measured Value of Final State

	1	2	3	4	5	6	7	8	9	10
$T(m_t)$	1195.1	975.2	765.2	561.6	1154.9	899.3	723.3	545.8	738.1	728.3
$P(m_p)$	0.167	0.137	0.109	0.103	0.167	0.137	0.109	0.103	-	-
$V(m_v)$	(0.109,0.356)	(-0.109,0.356)	-	-	-	-	-	-	-	-

Table. 2: Initial Value of Instrumentations

	1	2	3	4	5	6	7	8	9	10
$T(m_t)$	1217.5	977.1	747.7	544.2	1139.7	877.2	706.9	530.0	715.2	706.5
$P(m_p)$	0.113	0.094	0.075	0.070	0.113	0.093	0.075	0.070	-	-
$V(m_v)$	(0.081,0.280)	(-0.080,0.280)	-	-	-	-	-	-	-	-

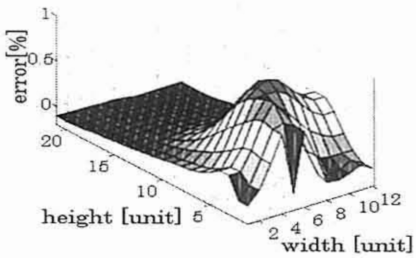


Fig. 31: Error of Temperature

The error between actual and estimated temperature distribution is less than 1 percent. Consequently, temperature distribution in reactor furnace is estimated by the control system.

Additionally, since the average temperature difference is expressed on iterations, equation (12) is defined.

$$f' = \sqrt{\frac{1}{252}\sum_{i=1}^{21}\sum_{j=1}^{12}(T_d(i,j) - T_g^l(i,j))^2} \qquad (12)$$

Value of f' is shown in Fig. 27. Since value of f' decreases, it finds that estimated temperature distribution is matching with temperature distribution in reactor furnace.

Descriptions above are summarized in Fig. 32. The components in Fig. 32 are Fig. 13, Fig. 22, Fig. 28, Fig. 27 and Table 1, 2. Table 1 shows measured values at initial state. Table 2 shows measured values at final state.

At initial state, heat balance was shifted to left hand side and desired heat balance is centralized. To attain the desired distribution furnace center of heat was moved to right hand side. As the resule, measured temperatures along the wall of left hand side decreased. On the contrary that alomg right hand side has been increased.

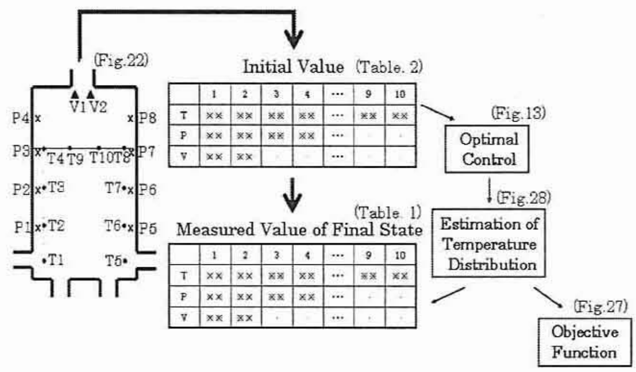


Fig. 32: Error of Temperature

6 Conclusion

In this paper, the model of reactor furnace consists of gas flow, gas temperature and solid temperature calculation are described. And gas temperature, solid temperature, gas flow and pressure distribution in reactor furnace are calculated using this model. Moreover, the control system in order to adjust to temperature distribution of reactor furnace is studied using the sequential quadratic programming method. After operation of the conrol, temperature distribution in reactor furnace is matching with desired temperature distribution. When gas volume is adjusted dynamically, necessary time until temperature distribution in reactor furnace is controlled to desired temperature distribution is reduced 50 percent. Additionally, when the number of instrumentations is limited, the control system accompanied with estimation function of inner temperature distribution is constructed. Temperature distribution in reactor furnace is made sure by simulation. However, optimization of the location of instrumentations has not been examined yet. Further, examination about this will be made in the future.

Also, the construction of control system considered the production of pig-iron is the important issue in the future.

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