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Hot Stove Combustion Pattern Optimization

Akira FUJII*
Noriko FUJII
Hiroshi MIYAZAKI
Masahiro ITO
Motoki HONDA

Abstract

As hot stove is a process that requires a large amount of heat energy, so conducting energy saving operations, which minimize the energy consumption and maximize the heat efficiency, is desired. We have developed a new method of optimizing the combustion pattern by which the heat efficiency can be maximized. In this method, the hot stove control simulator and the genetic algorithm (GA) are used. The simulator consists of physical and control models, so it can predict the dynamic change of the process states accurately when the candidate patterns are given by GA. The method has been proven to improve the heat efficiency through the actual control tests.

1. Introduction

Hot stove is a plant process that supplies a large volume of hot air to blast furnaces continuously and consumes a great amount of energy in iron and steel works. Therefore, energy-saving operation that maximizes heat efficiency is required. The hot-stove-operation technology introduced hereafter is able to determine the operation condition that improves the heat efficiency by predicting with high accuracy the future process state immediately by using a hot stove control simulator that simulates the dynamic characteristics of the entire hot stove process.

This article reports a method of determining efficiently the combustion pattern (target control value pattern for combustion control operation during a combustion period) that maximizes the heat efficiency while maintaining the plant constraint by combining a hot stove control simulator and an optimizing algorithm.

2. Hot Stove Process

As shown in **Fig. 1**, hot stove consists of a combustion chamber, a checker chamber, a mixing chamber, and the piping connecting such chambers. In the operation of the hot stove, a combustion period and a blast period, each having a fixed time length, are repeated periodically.

During the combustion period in the operation of the hot stove, fuel gas and air that are flow-controlled independently are supplied to the combustion chamber, and the high temperature gas produced by combustion therein is sent to the checker chamber. The ratio of the fuel gas flow rate and the air flow rate is controlled by the feedback from the dome temperature so that the dome temperature is controlled to a predetermined target value. The heat of the high temperature gas is stored in the layered checker brick through heat exchange, and the gas after the heat exchange is discharged outward as exhaust gas from the bottom of the checker chamber.

During the blast period, contrarily to the combustion period, flow-controlled air is fed from the bottom of the checker chamber, and heat is exchanged between the checker brick and the air. The high temperature air flows out from the upper checker chamber and is blown into the blast furnace as hot air through the blast main pipe via the combustion chamber and the mixing chamber.

Three or four hot stoves of this type have been built and each operation cycle of the blast period and the combustion period is staggered as shown in **Fig. 2** so that hot air can be blown into the

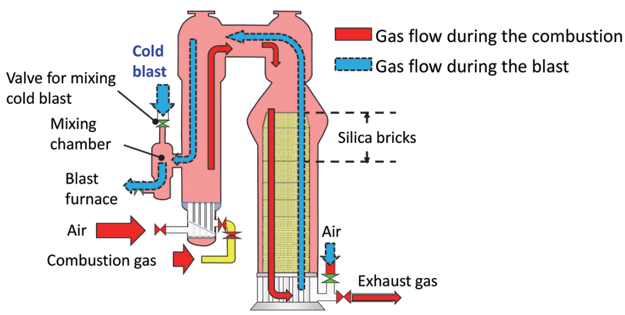

Fig. 1 Image of hot stove

* Senior Manager, Systems & Control Technology Dept., Systems & Control Engineering Div., Plant Engineering and Facility Management Center
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

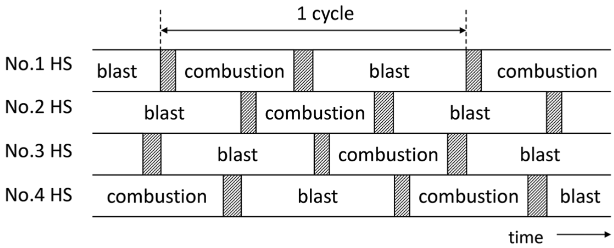

Fig. 2 Example of a hot stove operation cycle

blast furnace continuously.[1, 2)]

3. Hot Stove Control Simulator

The simulator herein used consists of two models. The first is a hot stove process model that models the dynamic characteristics of heat transmission and combustion in the hot stove process. The second is a hot stove control model that has the control functions of the process computer and the instrumentation system actually equipped in the real plant.

3.1 Hot stove process model

The process model consists of the hot stove body comprising combustion chambers, checker chambers, mixing chambers, and a blast main pipe, and is modelled based on the real plant specification (**Fig. 3**).

A combustion model of fuel gas (BFG, COG, LDG, mixed gas, etc.) is built in the combustion chamber model and calculates the temperature and the amount of the hot gas produced by combustion. For instance, the temperature of the combustion gas when BFG and COG are used as fuel gas is expressed by the following expressions.[3)]

$$T_{\text{th}} = \frac{F_{\text{MIX}} \cdot H_{\text{l,MIX}}}{F_{\text{COMB}} \cdot C_{\text{p,MIX}(T_{\text{th}})}} + T_{\text{MIX,pre}} \tag{1}$$

$$F_{\text{MIX}} = F_{\text{BFG}} + F_{\text{COG}} \tag{2}$$

where:
T_{th}: Combustion gas temperature, F_{MIX}: Fuel gas flow rate
F_{BFG}: BFG flow rate, F_{COG}: COG flow rate
F_{COMB}: Combustion gas flow rate, $H_{\text{l,MIX}}$: Fuel gas calorific value
$C_{\text{p,MIX}}$: Combustion gas specific heat at constant pressure
$T_{\text{MIX,pre}}$: Fuel gas temperature before combustion

On the other hand, the checker chamber is assumed to be of a concentric cylindrical structure consisting of the checker brick in the inside layer and the chamber wall in the outside layer. Based on the assumption, a heat transfer model of a cylindrical two-dimensional unsteady distributed parameter system was developed considering the heat conduction in the radial direction of the checker chamber with the heat radiation to open air. The heat exchange between the combustion gas and the checker brick was modelled based on convective flow heat transmission and radiation heat transmission, and the heat exchange between the solid bodies of the checker brick and the furnace wall structure was modelled based on heat transmission through heat conduction.

As an example, the checker chamber model is shown in **Fig. 4**. When the radial direction of the chamber is spatially broken up into i elements and the height direction of the chamber is spatially broken up into j elements, the models of gas, checker brick, and the furnace wall structure are expressed by the following equations.[1–3)]

1) Gas model

$$\begin{aligned} &\rho_g(T_{\text{g,j}}) \cdot C_{\text{pg}}(T_{\text{g,j}}) \cdot S_{\text{g,j}} \cdot v_{\text{g,j}}(t) \cdot \frac{dT_{\text{g,j}}(t)}{dz} \\ &= K_{(\text{g},1),\text{j}} \cdot A_{(\text{g},1),\text{j}} \cdot \{T_{1,\text{j}}(t) - T_{\text{g,j}}(t)\} \\ &+ \varepsilon \cdot \sigma \cdot A_{(\text{g},1),\text{j}} \cdot \{(T_{1,\text{j}}(t) + 273.15)^4 - (T_{\text{g,j}}(t) + 273.15)^4\} \end{aligned} \tag{3}$$

2) Solid model (when i = 1, checker brick)

$$\begin{aligned} &\rho_1(T_{1,\text{j}}) \cdot C_{\text{p1}}(T_{1,\text{j}}) \cdot S_{1,\text{j}} \cdot z_{\text{j}}(t) \cdot \frac{dT_{1,\text{j}}(t)}{dt} \\ &= K_{(\text{g},1),\text{j}} \cdot A_{(\text{g},1),\text{j}} \cdot \{T_{\text{g,j}}(t) - T_{1,\text{j}}(t)\} \\ &+ \varepsilon \cdot \sigma \cdot A_{(1,2),\text{j}} \cdot \{(T_{1,\text{j}}(t) + 273.15)^4 - (T_{2,\text{j}}(t) + 273.15)^4\} \end{aligned} \tag{4}$$

3) Solid model (when i = 2, 3,….7, furnace wall structure)

$$\begin{aligned} &\rho_{\text{i}}(T_{\text{i,j}}) \cdot C_{\text{pi}}(T_{\text{i,j}}) \cdot S_{\text{i,j}} \cdot z_{\text{j}}(t) \cdot \frac{dT_{\text{i,j}}(t)}{dt} \\ &= K_{(\text{i}-1,\text{i}),\text{j}} \cdot A_{(\text{i}-1,\text{i}),\text{j}} \cdot \{T_{\text{i}-1,\text{j}}(t) - T_{\text{i,j}}(t)\} \\ &- K_{(\text{i},\text{i}+1),\text{j}} \cdot A_{(\text{i},\text{i}+1),\text{j}} \cdot \{T_{\text{i,j}}(t) - T_{\text{i}+1,\text{j}}(t)\} \end{aligned} \tag{5}$$

where ρ: Density, C_{p}: Specific heat, S: Sectional area, v: Flow speed, T: Temperature, K: Heat transfer coefficient, A: Area of contact, ε: Thermal emissivity, z: Height, t: Time, g: Gas, σ: Stefan-Boltzmann constant.

3.2 Hot stove control model

A hot stove control model was developed and implemented in the simulator. The model consists of a model of a process computer

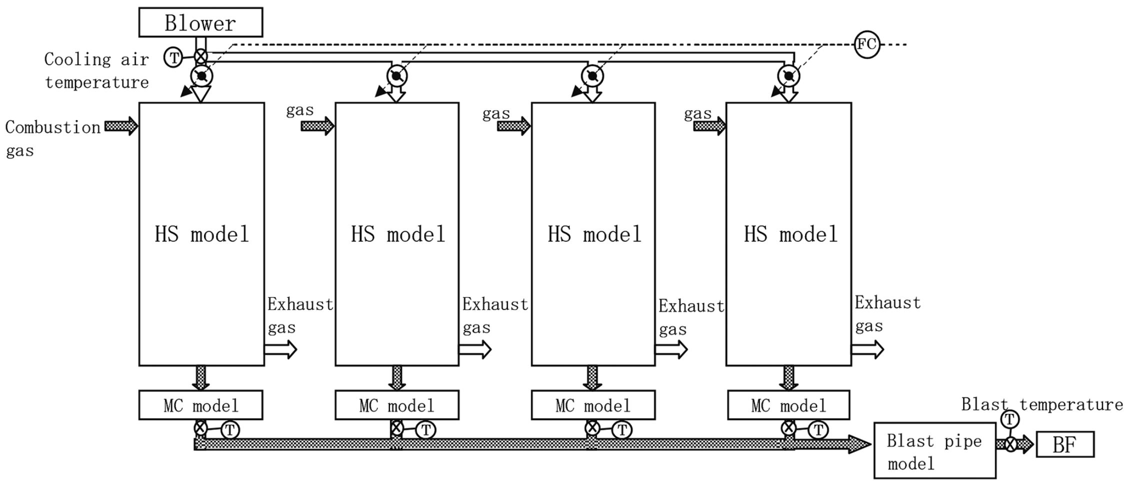

Fig. 3 Hot stove simulator model

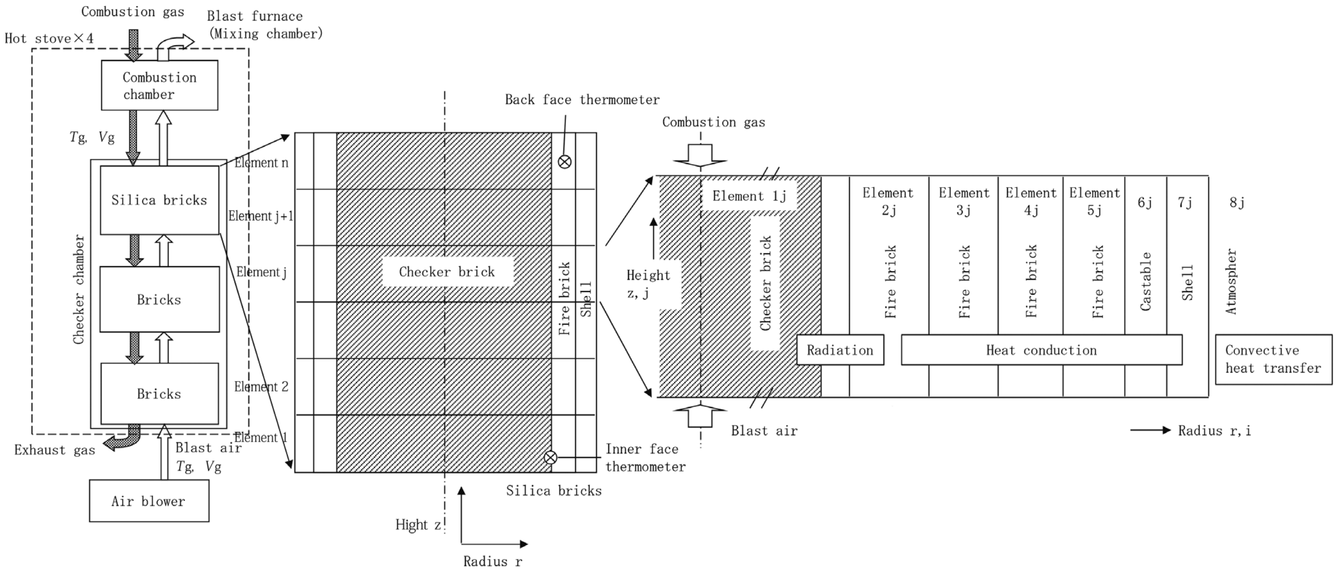

Fig. 4 Hot stove process model

control function that controls the total heat quantity input during the period from the start of combustion to the termination of combustion, and a model of instrumentation control function that controls the dome temperature and the fuel gas flow rate. By combining the process model of 3.1 with the control model, quantitative prediction and evaluation of the process state such as blast temperature, checker chamber silica brick temperature, and so on can be realized when various target values such as fuel gas flow rate are provided to the control model.

4. New Hot Stove Combustion Control Method

4.1 Improvement of hot stove combustion efficiency[3–6)]

By using the developed hot stove control simulator, an operation method that improves heat efficiency is determined. The heat efficiency is given by the following expression.

$$\text{Heat efficiency} = \frac{\text{Blast heat quantity input to blast furnace during blasting}}{\text{Heat quantity input to hot stove during combustion}} \cong \frac{Q_{out}}{Q_{str}+Q_{ex}} \tag{6}$$

where:
Q_{out}: Blast heat quantity
Q_{str}: Heat quantity stored in hot stove during combustion
Q_{ex}: Heat quantity discharged to outside as exhaust gas and radiation heat from hot stove

Since the blast heat quantity supplied to a blast furnace is determined by the operating condition of the blast furnace, it is known from Expression (6) that the heat efficiency is improved by storing sufficient heat quantity for the required blast heat quantity firstly and then by reducing the excessive input heat quantity.

As most of the excessive heat quantity not stored is discharged from the hot stove as exhaust gas heat quantity, the possibility of reducing the input heat quantity by reducing the exhaust gas heat quantity by enlarging the heat exchange efficiency between the combustion gas and the checker brick was studied. The efficiency of the heat exchange between the combustion gas and the checker brick depends on the flow rate and the temperature of the combustion gas. Therefore, these values have to be controlled to improve the heat efficiency.

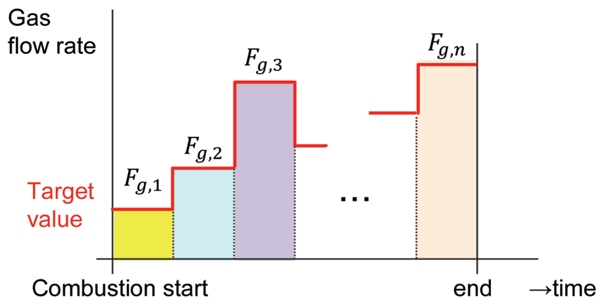

Fig. 5 Combustion pattern (example of gas flow rate)

In the conventional combustion control, the combustion gas flow rate and the temperature are controlled to constant target values from the start of combustion to the termination of combustion. In the new combustion control method, the targeted combustion control values for operation such as fuel gas calorific power, fuel gas flow rate, and the dome temperature are made variable during the combustion period. Namely, as in the case of the gas flow rate shown in **Fig. 5**, the time period from the start of combustion to the termination of combustion is divided into plural elements, and a combustion pattern is structured by setting an independent target value for the respective elements.

The objective of determining the combustion pattern that maximizes the control performance quantified by heat efficiency is the optimization problem to achieve the best control performance (hereinafter referred to as the optimized combustion pattern) by executing calculation using the hot stove control simulator to predict the change of the process state parameters by changing the combustion pattern. In the abovementioned procedure, by predicting the state of the process with the hot stove control simulator, satisfying the constrained conditions such as the checker brick temperature is guaranteed.

4.2 Whole control structure[7–9)]

As shown in **Fig. 6**, the whole control structure of the new con-

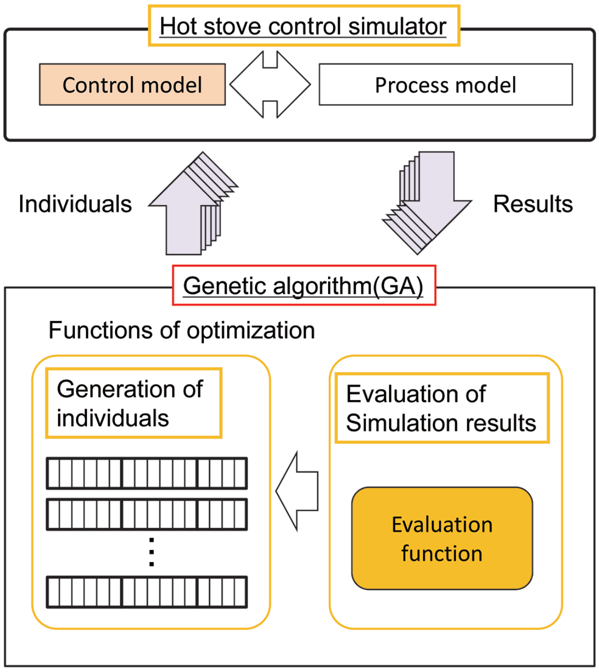

Fig. 6 Structure of combustion pattern optimization

trol method consists of the hot stove control simulator and the optimization algorithm. As the optimization of the combustion pattern using the hot stove control simulator is basically a nonlinear optimization problem, it was decided to adopt the genetic algorithm (GA), one of the heuristic methods, to address this problem.

Specifically, first solution candidates (individuals) of the combustion pattern are generated by GA, and the hot stove control simulator predicts the process state when the hot stove is operated based on an individual. Next, GA calculates the value of the evaluation function with the obtained predicted result. The individuals with a small evaluation value are extracted and genetic manipulation (crossover or mutation) is applied to the remaining individuals to generate solution candidates of the next generation. This calculation is repeated for GA generation many times. The solution that shows the smallest evaluation value is determined as the optimum combustion pattern.

4.3 Method of applying genetic algorithm[7–9)]

To determine the optimum combustion pattern that maximizes the heat efficiency by using the abovementioned control structure and GA, the solution candidates and the evaluation function are set as below.

(1) Pattern solution candidate

As shown in **Fig. 7**, the group of the following controlled valuables constitutes one individual (pattern solution candidate); gas flow rate (F_g), dome temperature (T_d), gas calorific power (C_a), etc.

Namely, an individual is defined as a group of the numerical values as represented by the expression (7) and GA is applied to the combinational optimization problem.

$$\text{Individual} = [\,F_{g,1}\ F_{g,2}\ \dots\ F_{g,n}\ T_{d,1}\ T_{d,2}\ \dots\ T_{d,m}\ C_{a,1}\ C_{a,2}\ \dots\ C_{a,p}\,] \quad (7)$$

where every numerical value that constitutes the individual has its own upper and lower limits.

$$F_{g,\min} \le F_{g,i} \le F_{g,\max}\,,\quad i = 1, \dots, n \quad (8)$$
$$T_{d,\min} \le T_{d,j} \le T_{d,\max}\,,\quad j = 1, \dots, m \quad (9)$$
$$C_{a,\min} \le C_{a,k} \le C_{a,\max}\,,\quad k = 1, \dots, p \quad (10)$$

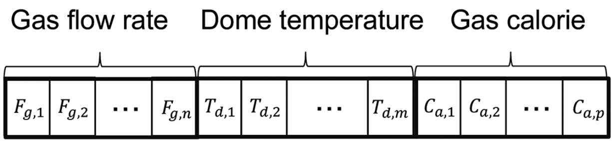

Fig. 7 Example of the individual

These upper and lower limits are the constrained conditions specified as follows: gas flow rate restricted by the gas supply blower capacity, dome temperature restricted by the upper limit temperature set for equipment protection and environmental protection, and the gas calorific power determined by steel works energy supply balance and or energy cost.

(2) Evaluation function

The evaluation function is expressed by the following expressions by using the exhaust gas temperature that evaluates the heat efficiency and the silica brick temperature restricted by the equipment condition. The pattern that minimizes the evaluation function is selected as the optimized combustion pattern with target control values.

$$Q = w_1 \cdot P_1 + w_2 \cdot (max\,[cr - P_2, 0]) \quad (11)$$

where:

$$P_1 \le P_{1,\max} \quad (12)$$

P_1: Exhaust gas temperature

$P_{1,\max}$: Exhaust gas upper limit temperature restricted by equipment condition

P_2: Silica brick temperature

cr: Silica brick lower limit temperature restricted by equipment condition

w_1, w_2: Weighting factor

5. Example of On-site Test Result[7–9)]

In **Fig. 8**, an example of an optimum solution determined by the abovementioned method is shown. From among a number of solution candidates, the optimum solution that minimizes the exhaust gas temperature after clearing the constrained condition of silica brick temperature is determined. The optimum combustion pattern obtained in this method was calculated off-line and was applied to an on-site test (**Fig. 9**). As hot stove control simulation conditions, the latest operation data of blast temperature and the blast flow rate are input, and then the off-line optimization of the combustion pattern using the abovementioned method is executed. The optimum combustion pattern so obtained is applied to the actual hot stove combustion control.

An example of the results of the on-site test is shown in **Fig. 10**. Maximization of the heat efficiency is a key index in control performance evaluation. As indicated by Expression (6) that the heat efficiency can be improved by reducing the exhaust gas heat quantity discharged from the hot stove, reduction of the exhaust gas heat quantity was specifically studied. The exhaust gas heat quantity is expressed by the following expression.

Exhaust gas heat quantity = Exhaust gas specific heat
× Exhaust gas flow rate × Exhaust gas temperature (13)

As indicated by Expression (13), when the exhaust gas flow rate remains the same, the lower the exhaust gas temperature is, the smaller the exhaust gas heat quantity becomes. Therefore, the exhaust gas temperature was used as the evaluation index. In the example of the result of the on-site test shown in Fig. 10, with the varying flow rate of the combustion gas that passes through the checker chamber and the combustion temperature during the com-

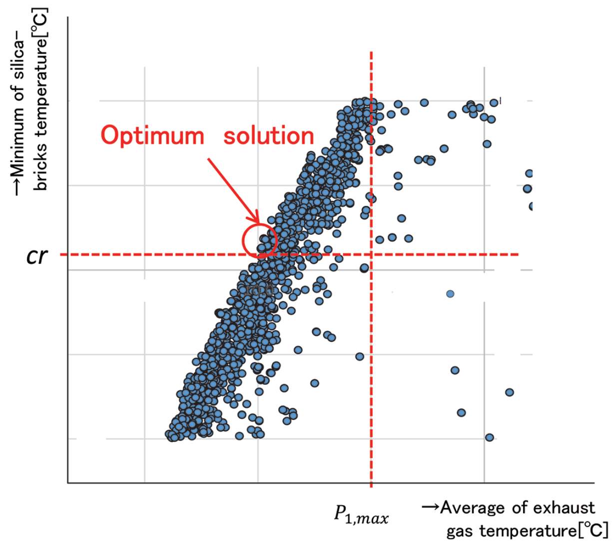

Fig. 8 Candidates and the optimum solution

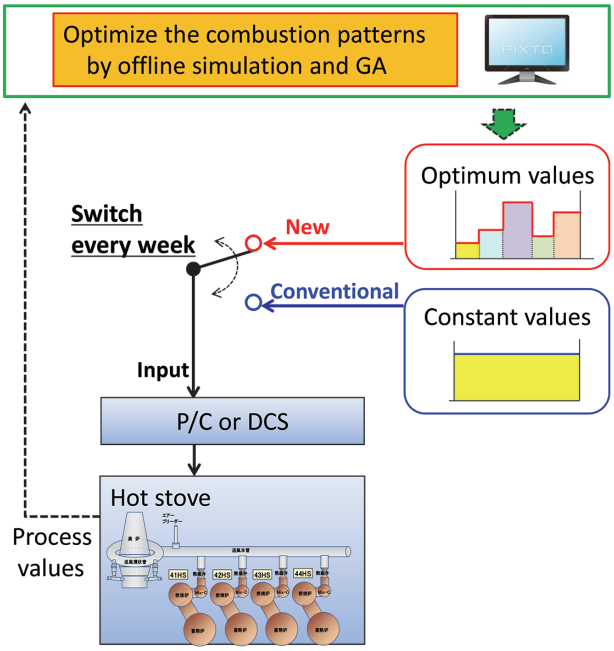

Fig. 9 System configuration for on-site test

bustion period, the exhaust gas temperature during the combustion period becomes lower by 5.6°C as compared with that of the conventional control, and improved heat efficiency was obtained as a result.

6. Conclusion

A new combustion control technology that optimizes the combustion pattern to improve the hot stove heat efficiency has been developed. Although in the conventional method, the target values of the combustion control were controlled at constant values, in this

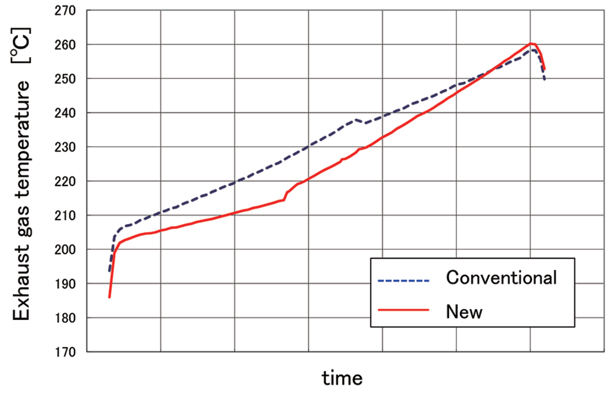

Fig. 10 Result of on-site test (exhaust gas temperature)

method, they were made variable from the start to the termination of combustion so that the new method was focused on enlarging the heat exchange efficiency between the combustion gas and the checker brick by varying the combustion gas flow rate and the temperature during the combustion period. GA was employed as the optimizing algorithm and the solution candidates generated by GA were evaluated by the hot stove control simulator. The simulator consisted of the combination of a physical model that models the dynamic characteristics of the entire hot stove and a model that models the control functions of instrumentation and process computers. By predicting the process state of the hot stove in future, satisfying the constrained conditions such as checker brick temperature and or exhaust gas temperature is guaranteed.

As a result of an on-site test using the optimum combustion pattern determined by this method, the exhaust gas temperature during the combustion period was lowered as compared with that of the conventional method, and improved heat efficiency was obtained as a result. Presently, this method is practically being used in the hot stoves of Nippon Steel & Sumitomo Metal Corporation.

References

1) Ito, M., Fujii, A., Ueno, T.: Seigi 134-1-5: Development of Hot Stove Process Model. The Iron and Steel Institute of Japan 134th Control Technology Subcommittee, Tokyo, 2005-11, Private Note
2) Ito, M., Ueno, T.: Development of Process Simulator for Hot-blast Stove. The Iron and Steel Institute of Japan 153th Spring Meeting, 20 (2), 303 (2007)
3) Takahashi, N., Fujii, A., Honda, M.: Development of Hot Stove Combustion Control. Institute of Electrical Engineers of Japan Monozukuri Workshop, MKZ-13-009, 2013
4) Takahashi, N., Fujii, A., Honda, M.: Seigi 148-1-5: Development of Hot Stove Combustion Control. The Iron and Steel Institute of Japan 148th Control Technology Subcommittee, Tokyo, 2012-11, Private Note
5) Takahashi, N., Fujii, A., Honda, M.: Development of Hot Stove Combustion Control. The Iron and Steel Institute of Japan 165th Spring Meeting, 26 (1), 131 (2013)
6) Japanese Patent Publication: JP4734014, 28th of April, 2011
7) Takahashi, N., Fujii, A.: Seigi 154-Sei-1: Development of Hot Stove Combustion Pattern Optimization. The Iron and Steel Institute of Japan 154th Control Technology Subcommittee, Tokyo, 2015-11, Private Note
8) Takahashi, N., Fujii, A.: Development of Hot Stove Combustion Pattern Optimization. The Iron and Steel Institute of Japan 171th Spring Meeting, 29 (1), 131 (2016)
9) Japanese Patent Publication: JP5803810, 11th of September, 2015


Akira FUJII
Senior Manager
Systems & Control Technology Dept.
Systems & Control Engineering Div.
Plant Engineering and Facility Management Center
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511


Noriko FUJII
Manager
Systems & Control Technology Dept.
Systems & Control Engineering Div.
Plant Engineering and Facility Management Center


Hiroshi MIYAZAKI
Senior Manager
Systems & Control Technology Dept.
Systems & Control Engineering Div.
Plant Engineering and Facility Management Center


Masahiro ITO
Senior Manager
Systems & Control Technology Dept.
Systems & Control Engineering Div.
Plant Engineering and Facility Management Center


Motoki HONDA
Senior Manager
Ironmaking Technical Dept.
Ironmaking Div.
Oita Works