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(71) Applicant: **JFE Steel Corporation**
Tokyo 100-0011 (JP)

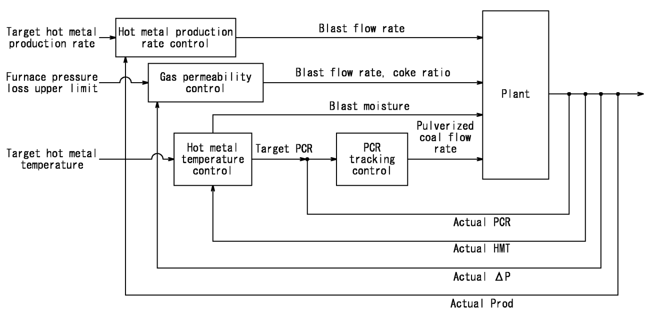
(72) Inventors:
- **HASHIMOTO Yoshinari**
  Tokyo 100-0011 (JP)
- **MASUDA Ryosuke**
  Tokyo 100-0011 (JP)
- **YAMATO Genya**
  Tokyo 100-0011 (JP)
- **KIZU Takeru**
  Tokyo 100-0011 (JP)

(74) Representative: **Scott, Stephen John**
YUJA IP LAW
4 Centenary House
The Avenue
York YO30 6AU (GB)

(54) PROCESS CONTROL METHOD, BLAST FURNACE OPERATION METHOD, MOLTEN PIG IRON PRODUCTION METHOD, AND PROCESS CONTROL APPARATUS

(57) A method of controlling a process, a method of operating a blast furnace, a method of producing hot metal, and a process control unit that can suppress variation of the hot metal temperature while reducing the reducing agent ratio in a blast furnace are provided. The method of controlling a process includes a response prediction step of determining a predicted value of a future hot metal temperature using a physical model capable of calculating conditions inside a blast furnace, and a operation amount determination step of determining a deviation between a target value and the predicted value of the hot metal temperature determined in the response prediction step, and determining operation amounts of a pulverized coal ratio and a blast moisture to minimize or maximize an evaluation function having a term corresponding to the deviation and a term for reducing a reducing agent ratio or the blast moisture.

FIG. 2



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Description

TECHNICAL FIELD

[0001] The present disclosure relates to a method of controlling a process, a method of operating a blast furnace, a method of producing hot metal, and a process control unit.

BACKGROUND

[0002] The hot metal temperature (HMT) is an important control index in a blast furnace process of the steelmaking industry and is controlled mainly by adjusting the pulverized coal ratio and the blast moisture. In recent years, blast furnace operations have been conducted under a set of conditions including a low coke ratio and high pulverized coal ratio in order to rationalize raw fuel costs. This approach can easily lead to furnace instability. It is therefore necessary to reduce the variation in hot metal temperature.

[0003] The blast furnace process is also characterized by a large heat capacity of the entire process and a long time constant of response to action, because operations are performed in a solid-filled state. Furthermore, it may take several hours, for example, for the raw material charged at the top of the furnace to descend to the bottom of the furnace. Therefore, appropriate operations based on predictions of future furnace heat are necessary to control the hot metal temperature.

[0004] To take the delayed response derived from the long time constant of the blast furnace into consideration, one method of controlling a blast furnace based on predictions is to use a physical model, such as the one in Patent Literature (PTL) 1.

CITATION LIST

Patent Literature

[0005] PTL 1: JP H11-335710 A

SUMMARY

(Technical Problem)

[0006] Here, the recent social demand for CO_2 reduction has led to demand for a reduction in the reducing agent ratio (the sum of the coke ratio and the pulverized coal ratio) in the blast furnace process. To reduce the reducing agent ratio, it is effective to reduce the blast moisture blown into the furnace or to reduce the furnace heat loss, so that an excess heat source is not consumed. However, in the blast furnace process, the hot metal temperature needs to be controlled, and the production rate of hot metal (hereinafter referred to as "hot metal production rate") needs to be kept near the target value. Therefore, operations tend to be performed on the pulverized coal ratio and blast moisture, with priority given to reducing hot metal temperature variation, rather than reducing the reducing agent ratio. Also, PTL 1 discloses a technique for controlling the hot metal temperature only and does not propose a control method that takes into consideration reduction of the reducing agent ratio.

[0007] It is an aim of the present disclosure, conceived to solve the above-described problems, to provide a method of controlling a process, a method of operating a blast furnace, a method of producing hot metal, and a process control unit that can suppress variation of the hot metal temperature while reducing the reducing agent ratio in a blast furnace.

(Solution to Problem)

[0008]

(1) A method of controlling a process according to an embodiment of the present disclosure includes

a response prediction step of determining a predicted value of a future hot metal temperature using a physical model capable of calculating conditions inside a blast furnace; and

a operation amount determination step of determining a deviation between a target value and the predicted value of the hot metal temperature determined in the response prediction step, and determining operation amounts of a pulverized coal ratio and a blast moisture to minimize or maximize an evaluation function having a term corresponding to the deviation and a term for reducing a reducing agent ratio or the blast moisture.

(2) As an embodiment of the present disclosure, in (1),
in the response prediction step, the predicted value of the future hot metal temperature is determined, using the physical model, based on a predicted value of a future hot metal temperature for a case in which a current manipulated variable is maintained and a predicted value of a hot metal temperature for a case in which the current manipulated variable is changed.
(3) As an embodiment of the present disclosure, in (1) or (2),
in the operation amount determination step, the evaluation function is a quadratic function with respect to unknown variables under a linear constraint with respect to the unknown variables, taking the operation amounts of the pulverized coal ratio and the blast moisture as the unknown variables to be determined, and the unknown variables are determined using the evaluation function.
(4) As an embodiment of the present disclosure, any one of (1) to (3) further includes
a step of manipulating a blast flow rate so that a predicted value of a hot metal production rate matches a target value and manipulating a coke ratio so that a predicted value of gas permeability is equal to or less than an upper limit.
(5) A method of operating a blast furnace according to an embodiment of the present disclosure includes
changing operating conditions using manipulated variables manipulated by the method of controlling a process according to any one of (1) to (4).
(6) A method of producing hot metal according to an embodiment of the present disclosure includes
producing hot metal using a blast furnace operated by the method of operating a blast furnace according to (5).
(7) A process control unit according to an embodiment of the present disclosure includes

a memory configured to store a physical model capable of calculating conditions inside a blast furnace; and
a hot metal temperature controller configured to acquire a target hot metal temperature that is a target value of a hot metal temperature and calculate operation amounts of a pulverized coal ratio and a blast moisture so that the hot metal temperature becomes the target hot metal temperature, wherein
the hot metal temperature controller is configured to

determine a predicted value of a future hot metal temperature using the physical model, and
determine a deviation between the target value and the predicted value of the hot metal temperature, and
determine operation amounts of the pulverized coal ratio and the blast moisture to minimize or maximize an evaluation function having a term corresponding to the deviation and a term for reducing a reducing agent ratio or the blast moisture.

(Advantageous Effect)

[0009] According to the present disclosure, a method of controlling a process, a method of operating a blast furnace, a method of producing hot metal, and a process control unit that can suppress variation of the hot metal temperature while reducing the reducing agent ratio in a blast furnace can be provided.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] In the accompanying drawings:

FIG. 1 is a diagram illustrating manipulated variables and control variables in a blast furnace process;
FIG. 2 is a diagram illustrating a method of controlling a process according to an embodiment of the present disclosure;
FIG. 3 is a diagram illustrating input/output information of a physical model used in the present disclosure;
FIG. 4 is a diagram illustrating the results of a control simulation with simultaneous manipulation of the pulverized coal ratio and the blast moisture;
FIG. 5 is a diagram illustrating the results of a control simulation with manipulation of only the pulverized coal ratio (comparative example);
FIG. 6 is a diagram illustrating the effect of reducing the reducing agent ratio (RAR); and
FIG. 7 is a diagram illustrating a configuration example of a process control unit according to an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0011] A method of controlling a process, a method of operating a blast furnace, a method of producing hot metal, and a process control unit according to an embodiment of the present disclosure will be described below with reference to the drawings.

[0012] FIG. 1 illustrates the basic manipulated variables and control variables in a blast furnace process (processes in the operation of a blast furnace). Control variables are variables that should be controlled during operation, but which are difficult or impossible to manipulate directly and are thus changed via correlated manipulated variables. In the operation of a blast furnace, the pulverized coal ratio or blast moisture is mainly manipulated to set the hot metal temperature to a target value. To maintain good blast furnace permeability (gas permeability), the coke ratio or blast flow rate is mainly manipulated. In addition, to set the hot metal production rate to a target value, the blast flow rate is mainly manipulated. Here, the furnace pressure loss, which has a direct effect on blowouts, is used as the gas permeability in the present embodiment. The furnace pressure loss is the difference between the blast pressure and the furnace top pressure (pressure at the top of the furnace). Besides the furnace pressure loss, various other indices of permeability, such as permeability resistance and facing shaft differential pressure, exist. Therefore, another index of permeability may be used instead of the furnace pressure loss as the gas permeability, or a combination of a plurality of indices of permeability may be used. The method of controlling a process according to the present embodiment focuses on the pulverized coal ratio and blast moisture, which are manipulated variables for controlling the hot metal temperature, and determines the optimal operation amounts of pulverized coal ratio and blast moisture so that the hot metal temperature is controlled while the reducing agent ratio is reduced.

[0013] FIG. 2 is a diagram illustrating processing in the method of controlling a process according to an embodiment of the present disclosure. In the method of controlling a process according to the present embodiment, the cascade control described in Reference 1 (JP 7107444 B2), for example, is used. In cascade control, control to calculate the target pulverized coal ratio (PCR) (the hot metal temperature control in FIG. 2) and control to calculate the pulverized coal flow rate required for the target PCR (the PCR tracking control in FIG. 2) are performed continuously. The hot metal temperature control can acquire a target hot metal temperature, which is a target value of the hot metal temperature (HMT), and can calculate a target PCR using the physical model described below. The hot metal temperature control not only calculates the target PCR (not only determines the operation amount of the pulverized coal ratio), but also calculates the operation amount of the blast moisture.

[0014] The method of controlling a process according to the present embodiment also includes hot metal production rate control and gas permeability control. The hot metal production rate control acquires a target hot metal production rate, which is a target value of the hot metal production rate (Production rate: Prod), and calculates a operation amount of the blast flow rate (BV) using the physical model described below. The gas permeability control acquires the furnace pressure loss upper limit, which is the upper limit of the furnace pressure loss (ΔP), and calculates the operation amounts of the blast flow rate and coke ratio using the physical model described below. Here, the actual values (which can be observed or calculated) at the plant that includes the blast furnace may be provided as feedback for purposes such as updating the physical model used in each control. In the example in FIG. 2, the actual values of pulverized coal ratio (PCR), hot metal temperature (HMT), furnace pressure loss (ΔP), and hot metal production rate (Prod) are indicated as actual PCR, actual HMT, actual ΔP, and actual Prod, respectively. The mapping between control variables and correlated manipulated variables in the blast furnace process is not limited to the examples illustrated in FIGS. 1 and 2. For example, in the hot metal production rate control, the enrichment oxygen flow rate can be manipulated instead of the blast flow rate.

[0015] In the present embodiment, during construction of the multi-variable control system illustrated in FIG. 2, individual controllers (hot metal temperature control, gas permeability control, and hot metal production rate control) are constructed to control the hot metal temperature (HMT), furnace pressure loss (ΔP), and hot metal production rate (Prod). The hot metal temperature is controlled by cascade control, which manipulates the blast humidity and manipulates the pulverized coal ratio (PCR) and pulverized coal flow rate. The gas permeability is controlled by manipulating the blast flow rate and the coke ratio. The hot metal production rate is controlled by manipulating the blast flow rate. Here, for example, in a case in which the blast flow rate is manipulated during hot metal production rate control, changes in the blast flow rate affect the hot metal temperature. This effect is reflected by the physical model in the hot metal temperature control and is calculated as the operation amount of the pulverized coal ratio or the blast moisture. By reflection of the calculated operation amount of the pulverized coal ratio or the blast moisture, the hot metal temperature is kept near the target value. Although individual controllers are constructed in the present embodiment as described above, it is possible to achieve control that takes into account the interference among the respective manipulated variables. That is, although the hot metal temperature control and hot metal production rate control, for example, interfere with each other, the control system is constructed to have disturbance elimination characteristics whereby fluctuations based on the manipulation of one manipulated variable are absorbed by manipulation of another manipulated variable, thereby reducing the effects of interference. The same is also true for gas permeability control.

[0016] In the method of controlling a process according to the present embodiment, a physical model of the blast furnace based on reaction kinetics is used to predict the future hot metal temperature and hot metal production rate, and the amount of change in the pulverized coal ratio and the blast moisture is determined so that the predicted values are near the target values. By using quadratic programming to minimize an evaluation function that takes the reducing agent ratio into account when determining the operation amount, it is possible both to reduce the reducing agent ratio and suppress variation in the hot metal temperature. An outline of the processing flow in the method of controlling a process according to the present embodiment is illustrated in steps 1 to 3 below.

[0017] First, as step 1, a future hot metal temperature is predicted using a physical model. Step 1 is the response prediction step. In the response prediction step, the predicted value of the future hot metal temperature is determined, using the physical model, based on a predicted value of a future hot metal temperature for a case in which a current manipulated variable is maintained and a predicted value of the hot metal temperature for a case in which the current manipulated variable is changed. The predicted value of the future hot metal temperature for the case in which the current manipulated variable is maintained is a free response, described below. The predicted value of the hot metal temperature for the case in which the current manipulated variable is changed is the step response, described below, in the present embodiment, but this configuration is not limiting.

[0018] Next, as step 2, the manipulated variable is manipulated using quadratic programming so that the predicted value of the hot metal temperature in step 1 matches the target value, and so that the reducing agent ratio is minimized. Step 2 is the operation amount determination step, in which the deviation between the predicted value and the target value is determined, the operation amounts to eliminate the deviation are determined, and the manipulated variables are adjusted. In the present embodiment, the manipulated variables are the pulverized coal ratio and the blast moisture.

[0019] As step 3, to simulate the actual operation of the blast furnace, the blast flow rate may be manipulated so that the predicted value of the hot metal production rate matches the target value, and at least the coke ratio may be manipulated so that the predicted value of the gas permeability is equal to or less than an upper limit. In the present embodiment, the gas permeability is the furnace pressure loss, and if the predicted value of the furnace pressure loss exceeds a set upper limit, the gas permeability state is judged to be abnormal. In a case in which the gas permeability state is judged to be abnormal, an operation to increase the coke ratio may be performed. In a case in which the gas permeability state is judged not to be abnormal, i.e., the predicted value of the furnace pressure loss is equal to or less than the upper limit, an operation to reduce the coke ratio may be performed. Manipulation of the blast flow rate and the coke ratio by step 3 is a disturbance from the perspective of the hot metal temperature control. As described below, it was verified by simulation that the effects of this disturbance can be counteracted by manipulating the pulverized coal ratio and the blast moisture.

[0020] The physical model used in the present disclosure is the same as the model of the method described in Reference 2 (Michiharu Hatano et al., "Investigation of Blow-in Operation through the Blast Furnace Dynamic Model", Tetsu-to-Hagane, vol. 68, p. 2369). In other words, use is made of a physical model that consists of a set of partial differential equations taking into account physical phenomena such as ore reduction, heat exchange between ore and coke, and melting of ore, and that can calculate the conditions inside the blast furnace under non-steady state conditions. This physical model is also referred to below as a non-steady state model.

[0021] As illustrated in FIG. 3, among the input variables given to the non-steady state model, the main input variables that vary with time are the blast flow rate, enrichment oxygen flow rate, pulverized coal flow rate, blast moisture, blast temperature, coke ratio, and furnace top pressure. These input variables are the manipulated variables or manipulation factors of the blast furnace. The blast flow rate, enrichment oxygen flow rate, and pulverized coal flow rate are, respectively, the volumes of air, oxygen, and pulverized coal delivered to the blast furnace. The blast moisture is the humidity of the air delivered to the blast furnace. The blast temperature is the temperature of the air delivered to the blast furnace. The coke ratio is the coke ratio at the top of the furnace and is the weight of coke used per ton of hot metal produced.

[0022] The main output variables of the non-steady state model are the gas utilization ratio, the solution loss carbon content (solution loss carbon amount), reducing agent ratio, hot metal production rate, hot metal temperature, and furnace pressure loss. The non-steady state model can be used to calculate the hot metal temperature, hot metal production rate, and furnace pressure loss, which change moment by moment. While not being particularly limited, the time interval between calculations in the present embodiment is 30 minutes. The time difference between "t + 1" and "t" in the equations of the non-steady state model described below is 30 minutes in the present embodiment.

[0023] The non-steady state model can be expressed by Expressions (1) and (2) below.

[Math. 1]

$$x(t+1) = f\big(x(t), u(t)\big) \qquad (1)$$

$$y(t) = C\big(x(t)\big) \qquad (2)$$

[0024] Here, x(t) represents state variables calculated in the non-steady state model. State variables are, for example, the temperature of the coke, the temperature of the iron, the oxidation degree of the ore, and the rate of descent of the raw material. Here, y(t) represents control variables, i.e., the hot metal temperature, the hot metal production rate, and the gas permeability (furnace pressure loss). Here, u(t) represents the aforementioned input variables, which can be manipulated by the operator of the blast furnace. That is, the input variables are the blast flow rate BV(t), enrichment oxygen flow rate BVO(t), pulverized coal flow rate PCI(t), blast moisture BM(t), blast temperature BT(t), coke ratio CR(t), and furnace top pressure TGP(t). This can be expressed as u(t) = (BV(t), BVO(t), PCI(t), BM(t), BT(t), CR(t), TGP(t))^T.

[0025] First, a predictive calculation of the future control variables is made, assuming that the current values of the input variables are held constant. Taking the current time step, t_0, as 0, the future control variables are predicted using Expressions (3) and (4) below. The response $y_f(t)$ of the control variables determined in this way is called the free response.

[Math. 2]

$$x(t+1) = f\big(x(t), u(0)\big) \qquad (3)$$

$$y_f(t) = C\big(x(t)\big) \qquad (4)$$

[0026] Below, methods for determining the operation amounts of the current and future pulverized coal ratio (PCR) and blast moisture (BM) are described. An example of predicting two hours into the future will be explained. The unknown variables $\theta = (\Delta PCR_0, \Delta BM_0, \Delta PCR_1, \Delta BM_1)$ are introduced, and the operation amounts of the pulverized coal ratio (PCR) and blast moisture (BM) are determined by quadratic programming. The subscript 0 indicates the current value. Also, the subscript 1 indicates 2 hours later.

[0027] As an assumption for predictive control using this physical model, it may be assumed that the future hot metal temperature can be approximated by overlapping the response $y_f(t)$, which is the free response, and the step response. Furthermore, $y_{pre}(t)$, which is the predicted value of the hot metal temperature every 2 hours up to 10 hours ahead, is given by Expression (5) below.

[Math. 3]

$$\begin{pmatrix} y_{pre}(4) \\ y_{pre}(8) \\ y_{pre}(12) \\ y_{pre}(16) \\ y_{pre}(20) \end{pmatrix} = \begin{pmatrix} S_{PCR}(4) & S_{BM}(4) & 0 & 0 \\ S_{PCR}(8) & S_{BM}(8) & S_{PCR}(4) & S_{BM}(4) \\ S_{PCR}(12) & S_{BM}(12) & S_{PCR}(8) & S_{BM}(8) \\ S_{PCR}(16) & S_{BM}(16) & S_{PCR}(12) & S_{BM}(12) \\ S_{PCR}(20) & S_{BM}(20) & S_{PCR}(16) & S_{BM}(16) \end{pmatrix} \begin{pmatrix} \Delta PCR_0 \\ \Delta BM_0 \\ \Delta PCR_1 \\ \Delta BM_1 \end{pmatrix} + \begin{pmatrix} y_f(4) \\ y_f(8) \\ y_f(12) \\ y_f(16) \\ y_f(20) \end{pmatrix} \qquad (5)$$

[0028] Here, $S_{PCR}(t)$ is the amount of change in the hot metal temperature in a case in which the pulverized coal ratio (PCR) is manipulated by a unit amount (1 [kg/t]). $S_{BM}(t)$ is the amount of change in the blast moisture (BM) in a case in which the blast moisture is manipulated by a unit amount (1 [g/Nm^3]). S_{PCR} and S_{BM} can, for example, be determined by another physical model or a step response test during actual operation. The simulation results described in Reference 3 (Y. Hashimoto, Online prediction of hot metal temperature using transient model and moving horizon estimation. ISIJ Int. 2019, vol. 59, p. 1534) were used in the calculations in the present disclosure.

[0029] In the following, if Expression (5) is expressed as Expression (6) below using a step response matrix S, the deviation between the predicted value and the target value $y_{pre}(t)$ of the hot metal temperature is as in Expression (7).

[Math. 4]

$$y_{pre} = S\theta + y_f \qquad (6)$$

$$y_{pre} - y_{ref} = S\theta + \big(y_f - y_{ref}\big) = S\theta + \delta y \qquad (7)$$

[0030] Here, the deviation of the free response $y_f(t)$ from the target value $y_{pre}(t)$ is denoted as δy. The square of the deviation between the predicted value and the target value $y_{pre}(t)$ of the hot metal temperature is as in Expression (8) below.

[Math. 5]

$$\left|y_{pre} - y_{ref}\right|^2 = (\theta^T S^T + \delta y^T)(S\theta + \delta y) = \theta^T S^T S\theta + 2\delta y^T S\theta + const \qquad (8)$$

[0031] In order to achieve both reduction of hot metal temperature variation and minimization of the reducing agent ratio, the evaluation function J used in the quadratic programming includes, in addition to the first and second terms in Expression (8), a term to reduce the blast moisture (third term), as in Expression (9). The evaluation function J also includes a fourth term to suppress excessive manipulation.

[Math. 6]

$$J = \theta^T S^T S\theta + 2\delta y^T S\theta + a^T\theta + \theta^T R\theta \qquad (9)$$

[0032] Here, a and R are coefficients. It is known that when comparing the responsiveness of the hot metal temperature to changes in the pulverized coal ratio (PCR) and the blast moisture (BM), respectively, the blast moisture exhibits a more immediate response. However, it is necessary to increase the average value of the blast moisture to ensure manipulable regions in the increasing and decreasing directions, so that the blast moisture can be increased or decreased. Increasing the average value of the blast moisture causes heat absorption due to the steam decomposition reaction of the blast moisture. This leads to a problem in that more reducing material needs to be charged to compensate for the reduction in heat due to heat absorption. Therefore, the third term is introduced to limit the operation amount of the blast moisture, and the weights of ΔPCR and ΔBM included in the vector θ can be changed according to the magnitude of the elements of a coefficient vector a to adjust the distribution of the two manipulations.

[0033] In addition, θ is determined using Expression (9) under the constraints of Expressions (10) to (13) below.

[Math. 7]

$$PCR_{min} < PCR_{now} + \Delta PCR_i < PCR_{max} \qquad (10)$$

$$-\Delta PCR_{max} < \Delta PCR_i < \Delta PCR_{max} \qquad (11)$$

$$BM_{min} < BM_{now} + \Delta BM_i < BM_{max} \qquad (12)$$

$$-\Delta BM_{max} < \Delta BM_i < \Delta BM_{max} \qquad (13)$$

[0034] Here, the subscript i in Expressions (10) to (13) is 0 or 1. The subscript indicates the value of the current pulverized coal ratio (PCR) or blast moisture (BM). PCR_{max} and PCR_{min} are the upper and lower limits, respectively, of the target range of the pulverized coal ratio (PCR). ΔPCR_{max} is the upper limit of the magnitude of the allowed amount of change in the pulverized coal ratio (PCR). BM_{max} and BM_{min} are the upper and lower limits, respectively, of the target range of the blast moisture (BM). ΔBM_{max} is the upper limit of the magnitude of the allowed amount of change in the blast moisture (BM). The unknown variable θ is determined using quadratic programming so that the evaluation function J, which is a quadratic function with respect to the unknown variable θ, is minimized under the linear constraints for the unknown variable θ illustrated in Expressions (10) through (13). The control to determine the unknown variable θ using Expression (9) corresponds to the hot metal temperature control in FIG. 2.

[0035] In the present embodiment, the evaluation function J is designed to reduce the blast moisture in order to reduce the reducing agent ratio, but the same effect can be obtained by using an evaluation function J that directly reduces the reducing agent ratio, for example, by penalizing an increase in the pulverized coal ratio. Although the unknown variable θ is determined for the case in which the evaluation function J is minimized in the present embodiment, the evaluation function J may be designed so that the minimization of the deviation between the predicted value and target value of the hot metal temperature and the minimization of the reducing agent ratio (or blast moisture) correspond to the maximization of the evaluation function J. In other words, the operation amounts of the pulverized coal ratio and blast moisture may be determined so that the evaluation function J is minimized or maximized. Furthermore, a suboptimal value may be evaluated as the optimal value in the evaluation function J. In other words, even if the evaluation function J does not take the maximum or minimum value, the control objective can be treated as being achieved if the value of the evaluation function J is near the maximum value or the minimum value (if suboptimization is performed). Therefore, minimization or maximization of the evaluation function J may include not only the case of the value of the evaluation function J being maximized or minimized, but also the case of the value of the evaluation function J being near the maximum or minimum value.

[0036] To verify, by simulation, the reduction effect of the present disclosure on the reducing agent ratio under operating conditions close to actual operation, the manipulated variables (blast flow rate and coke ratio) were manipulated by the following method also for control variables other than the hot metal temperature (hot metal production rate and furnace pressure loss).

[0037] ΔBV, which is the operation amount of the blast flow rate (BV) [Nm^3/min], is determined by Expression (14) below, so as to eliminate the deviation between the target value and predicted value of the hot metal production rate.
[Math. 8]

$$\Delta BV = \frac{-b\left(Prod(t+T) - Prod_{ref}\right)}{S_{BV}} \qquad (14)$$

[0038] Here, Prod(t + T) is the predicted value of the hot metal production rate T steps ahead. As an example, T may be 4, which means that the predicted value is for 2 hours (30 minutes x 4) ahead. $Prod_{ref}$ is the target hot metal production rate (target value of the hot metal production rate). S_{BV} is the amount of change in the hot metal production rate in a case in which the blast flow rate (BV) is manipulated by a unit amount (1 [Nm^3/min]). S_{BV} can be determined by another physical model or a step response test during actual operation. Also, b is a coefficient and is a positive number. The control to determine ΔBV according to Expression (14) corresponds to the hot metal production rate control in FIG. 2.

[0039] The operation amounts of the coke ratio (CR) and blast flow rate (BV) are determined by comparison with the upper limit (threshold) for the furnace pressure loss (ΔP). In a case in which the furnace pressure loss (ΔP) exceeds the upper limit, the operation amounts are determined so as to increase the coke ratio while simultaneously decreasing the blast flow rate. This corresponds to operations for stabilizing the unloading of raw material during operation of the blast furnace. The operation amounts are determined so that the coke ratio is gradually reduced in a case in which the furnace pressure loss is equal to or less than the upper limit. As a general rule, control is performed so that the furnace pressure loss does not exceed the upper limit, but in a case in which the furnace pressure loss is equal to or less than the upper limit, the coke ratio can be gradually reduced to reduce the cost of operation. When such control is performed, the value of the furnace pressure loss remains near the upper limit. The control for determining the operation amounts of the coke ratio (CR) and blast flow rate (BV) by comparison with the upper limit of the furnace pressure loss corresponds to the gas permeability control in FIG. 2.

[0040] FIG. 4 is a diagram illustrating the results of a simulation based on the above process control. In other words, in the simulation in FIG. 4, the blast moisture (BM), pulverized coal ratio (PCR), blast flow rate (BV), and coke ratio (CR) were manipulated based on the predicted values, using the non-steady state model, of the hot metal temperature (HMT), hot metal production rate (Prod), and furnace pressure loss (ΔP), which is an example of the gas permeability. The target hot metal temperature was 1500 °C. The target hot metal production rate was 7 [t/min]. The upper limit of the furnace pressure loss was 100 [kPa].

[0041] As illustrated in FIG. 4, the hot metal temperature (HMT) is manipulated near the target value, and based on the evaluation function J illustrated in Expression (9), the blast moisture (BM) is kept near the lower limit while variation in the hot metal temperature is suppressed. The blast moisture being near the lower limit leads to a reduction in the reducing agent ratio, because heat absorption due to the steam decomposition reaction, which requires the charging of reduction material, is less likely to occur. The hot metal production rate (Prod) is controlled near the target value, and the furnace pressure loss (ΔP) is also kept at or below the upper limit.

[0042] For comparative verification, a simulation was performed for a comparative example in which only the pulverized coal ratio (PCR) was manipulated, whereas the blast moisture (BM) was not. FIG. 5 is a diagram illustrating the results of a simulation based on control in the comparative example. In the simulation in FIG. 5, the pulverized coal ratio (PCR), blast flow rate (BV), and coke ratio (CR) were manipulated based on the predicted values, using the non-steady state model, of the hot metal temperature (HMT), hot metal production rate (Prod), and furnace pressure loss (ΔP), which is an example of the gas permeability. The conditions of the simulation are the same as in FIG. 4, except for the blast moisture (BM). The blast moisture was set at a constant value of 15.5 [g/Nm^3].

[0043] FIG. 6 is a diagram illustrating the effect of reducing the reducing agent ratio ratio (RAR) and compares the change over time in the reducing agent ratio between the simulation results of FIG. 4 (method of controlling a process according to the present embodiment) and FIG. 5 (comparative example). As illustrated in FIG. 6, the average value of the reducing agent ratio in the method of controlling a process according to the present embodiment is lower than the average value of the reducing agent ratio in the comparative example. This demonstrates that the reducing agent ratio can be reduced by simultaneous manipulation of the pulverized coal ratio and the blast moisture. The reduction of the reducing agent ratio reduces the amount of oxygen (in units of oxygen atoms) [Nm^3/t], blown through the tuyere, required to produce 1 ton of hot metal. Therefore, the target hot metal production rate can be reached with a smaller blast flow rate. Consequently, the coke ratio is also reduced because of the resulting margin for pressure loss (see CR in FIGS. 3 and 4).

[0044] FIG. 7 is a diagram illustrating a configuration example of the process control unit 10 according to an embodiment. As illustrated in FIG. 7, the process control unit 10 according to the present embodiment includes a communication interface 11, a memory 12, and a controller 13. The controller 13 includes a hot metal temperature controller 14, a hot metal production rate controller 15, a gas permeability controller 16, and a PCR tracking controller 17. The process control unit 10 performs the aforementioned method of controlling a process. Here, the process control unit 10 may display information such as the operation amounts, for example, on a display such as a liquid crystal display in the case of manipulating the blast moisture, blast flow rate, coke ratio, or pulverized coal ratio.

[0045] The communication interface 11 is configured to include a communication module for communicating with a higher-level system. The higher-level system includes a process computer for managing the processes at the plant that includes the blast furnace. The communication interface 11 may include a communication module compatible with mobile communication standards such as 4G (4th Generation) and 5G (5th Generation), for example. The communication interface 11 may, for example, include a communication module compatible with a wired or wireless LAN standard. The controller 13 can acquire information such as the target hot metal temperature, target hot metal production rate, and upper limit of furnace pressure loss from the higher-level system via the communication interface 11. The controller 13 can also output, to the higher-level system via the communication interface 11, information on the manipulated variables that were manipulated, i.e., the manipulated variables in which the calculated operation amounts were reflected.

[0046] The memory 12 stores the aforementioned physical model. The memory 12 also stores programs and data related to control of the blast furnace process. The memory 12 may include any storage devices, such as semiconductor storage devices, optical storage devices, and magnetic storage devices. A semiconductor storage device may, for example, include a semiconductor memory. The memory 12 may include a plurality of types of storage devices.

[0047] The controller 13 controls and manages the process control unit 10 overall, including each functional component configuring the process control unit 10. The controller 13 may also acquire data used for control. In other words, the controller 13 may acquire the hot metal temperature, the hot metal production rate, and the gas permeability of the blast furnace via observed values or calculated values. The controller 13 is configured to include at least one processor, such as a CPU (Central Processing Unit), to control and manage various functions. The controller 13 may be configured by a single processor or a plurality of processors. The processor configuring the controller 13 may function as the hot metal temperature controller 14, the hot metal production rate controller 15, the gas permeability controller 16, and the PCR tracking controller 17 by reading and executing programs from the memory 12.

[0048] The hot metal temperature controller 14 acquires the target hot metal temperature that is the target value of the hot metal temperature and calculates operation amounts of the blast moisture and the pulverized coal ratio so that the hot metal temperature becomes the target hot metal temperature. The hot metal temperature controller 14 is the functional component that executes the "hot metal temperature control" in FIG. 2.

[0049] The hot metal production rate controller 15 acquires the target hot metal production rate that is the target value of the hot metal production rate and calculates the operation amount of the blast flow rate so that the hot metal production rate becomes the target hot metal production rate. The hot metal production rate controller 15 is the functional component that executes the "hot metal production rate control" in FIG. 2.

[0050] The gas permeability controller 16 acquires the upper limit of the gas permeability (the furnace pressure loss in the present embodiment) and calculates the operation amount of at least the coke ratio so that the gas permeability does not exceed the upper limit. The gas permeability controller 16 may further calculate the operation amount of the blast flow rate, as in the present embodiment. The gas permeability controller 16 is the functional component that executes the "gas permeability control" in FIG. 2.

[0051] The PCR tracking controller 17 acquires the target pulverized coal ratio (target PCR) determined by the hot metal temperature controller 14 and calculates the operation amount of the pulverized coal flow rate (PCI) so as to track the target PCR by PCR tracking control. The PCR tracking controller 17 is the functional component that executes the "PCR tracking control" in FIG. 2.

[0052] The hot metal temperature controller 14, the hot metal production rate controller 15, and the gas permeability controller 16 are individual controllers for controlling the hot metal temperature (HMT), hot metal production rate (Prod), and furnace pressure loss (ΔP), respectively. To explain with reference to the aforementioned steps 1 to 3, the hot metal temperature controller 14 performs step 1 (response prediction step) using the physical model to determine the predicted value of the hot metal temperature. The hot metal temperature controller 14 performs step 2 (operation amount determination step) to determine the operation amounts of the pulverized coal ratio and blast moisture. The hot metal production rate controller 15 performs step 3 to determine the operation amount of the blast flow rate so as to eliminate the deviation between the target value and predicted value of the hot metal production rate. The gas permeability controller 16 also performs step 3 to determine the operation amounts of the blast flow rate and the coke ratio so that the predicted value of the furnace pressure loss does not exceed the upper limit. Here, the hot metal temperature controller 14, the hot metal production rate controller 15, and the gas permeability controller 16, which are constructed as individual controllers as described above, are control systems with disturbance rejection characteristics whereby fluctuations based on the manipulation of manipulated variables in one controller are absorbed by manipulation of manipulated variables in another controller. Therefore, the hot metal temperature controller 14, the hot metal production rate controller 15, and the gas permeability controller 16 can reduce the effects of interference by manipulated variables from other controllers.

[0053] The method of controlling a process as performed by the process control unit 10 may be used as part of a method of operating a blast furnace. For example, the manipulated variables manipulated in the aforementioned method of controlling a process may be used to change the operating conditions in the operation of the blast furnace. Such a method of operating a blast furnace can also be performed as part of a process of producing hot metal. In a blast furnace, raw iron ore is melted and reduced to hot metal, which is then tapped as hot metal. The blast furnace may be operated according to this operating method.

[0054] The process control unit 10 may, for example, be realized by a separate computer from the process computer that controls the operation of the blast furnace, or by a process computer. The computer includes a memory and hard disk drive (storage device), a CPU (processing unit), and a display or other display device, for example. Various functions can be realized by organic cooperation between hardware, such as the CPU and memory, and programs. The memory 12 may, for example, be realized by a storage device. The controller 13 may, for example, be realized by a CPU.

[0055] As described above, the method of controlling a process, method of operating a blast furnace, method of producing hot metal, and process control unit 10 according to the present embodiment can, with the above-described configurations, suppress variation of the hot metal temperature while reducing the reducing agent ratio in a blast furnace.

[0056] While embodiments according to the present disclosure have been described with reference to the drawings and examples, it should be noted that various modifications and amendments may easily be implemented by those skilled in the art based on the present disclosure. Accordingly, such modifications and amendments are included within the scope of the present disclosure. For example, functions or the like included in each component, each step, or the like can be rearranged without logical inconsistency, and a plurality of components, steps, or the like can be combined into one or divided. Embodiments according to the present disclosure can also be realized as a program executed by a processor included in an apparatus or as a storage medium having the program recorded thereon. Such embodiments are also to be understood as included in the scope of the present disclosure.

[0057] The configuration of the process control unit 10 as illustrated in FIG. 7 is an example. The process control unit 10 need not include all of the components illustrated in FIG. 7. The process control unit 10 may include components other than those illustrated in FIG. 7. For example, the process control unit 10 may be configured to further include a display.

REFERENCE SIGNS LIST

[0058]

- 10 Process control unit
- 11 Communication interface
- 12 Memory
- 13 Controller
- 14 Hot metal temperature controller
- 15 Hot metal production rate controller
- 16 Gas permeability controller
- 17 PCR tracking controller

Claims

1. A method of controlling a process, the method comprising:

    a response prediction step of determining a predicted value of a future hot metal temperature using a physical model capable of calculating conditions inside a blast furnace; and

    a operation amount determination step of determining a deviation between a target value and the predicted value of the hot metal temperature determined in the response prediction step, and determining operation amounts of a pulverized coal ratio and a blast moisture to minimize or maximize an evaluation function having a term corresponding to the deviation and a term for reducing a reducing agent ratio or the blast moisture.

2. The method of controlling a process according to claim 1, wherein in the response prediction step, the predicted value of the future hot metal temperature is determined, using the physical model, based on a predicted value of a future hot metal temperature for a case in which a current manipulated variable is maintained and a predicted value of a hot metal temperature for a case in which the current manipulated variable is changed.

3. The method of controlling a process according to claim 1 or 2, wherein in the operation amount determination step, the evaluation function is a quadratic function with respect to unknown variables under a linear constraint with respect to the unknown variables, taking the operation amounts of the pulverized coal ratio and the blast moisture as the unknown variables to be determined, and the unknown variables are determined using the evaluation function.

4. The method of controlling a process according to any one of claims 1 to 3, further comprising a step of manipulating a blast flow rate so that a predicted value of a hot metal production rate matches a target value and manipulating a coke ratio so that a predicted value of gas permeability is equal to or less than an upper limit.

5. A method of operating a blast furnace, the method comprising changing operating conditions using manipulated variables manipulated by the method of controlling a process according to any one of claims 1 to 4.

6. A method of producing hot metal, the method comprising producing hot metal using a blast furnace operated by the method of operating a blast furnace according to claim 5.

7. A process control unit comprising:

a memory configured to store a physical model capable of calculating conditions inside a blast furnace; and
a hot metal temperature controller configured to acquire a target hot metal temperature that is a target value of a hot metal temperature and calculate operation amounts of a pulverized coal ratio and a blast moisture so that the hot metal temperature becomes the target hot metal temperature, wherein
the hot metal temperature controller is configured to

determine a predicted value of a future hot metal temperature using the physical model, and
determine a deviation between the target value and the predicted value of the hot metal temperature, and
determine operation amounts of the pulverized coal ratio and the blast moisture to minimize or maximize an evaluation function having a term corresponding to the deviation and a term for reducing a reducing agent ratio or the blast moisture.

FIG. 1

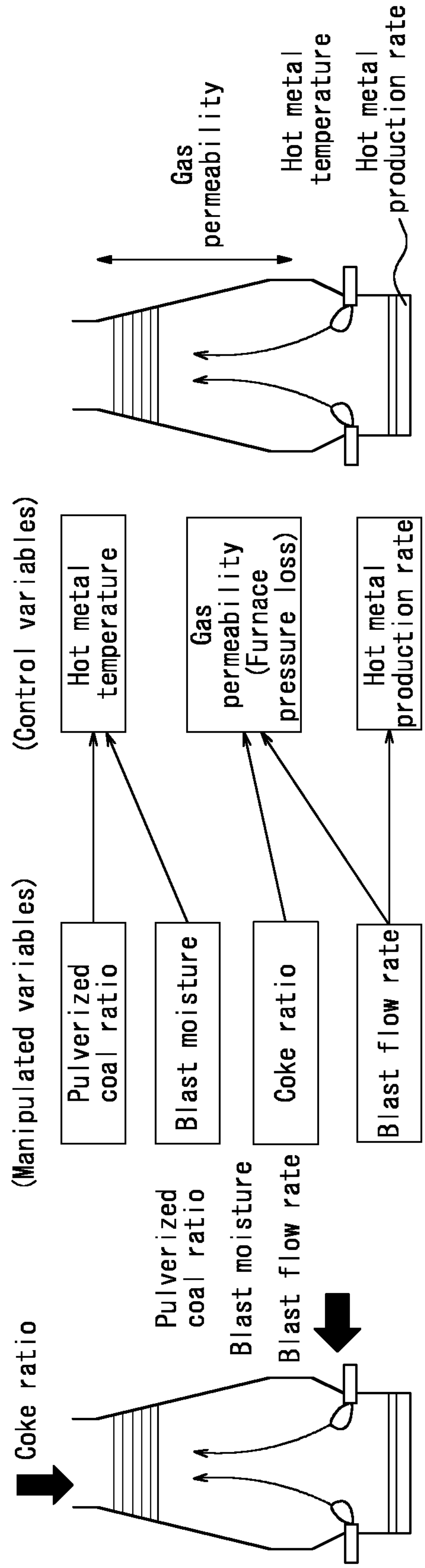

Coke ratio
Pulverized coal ratio
Blast moisture
Blast flow rate
(Manipulated variables)
Pulverized coal ratio
Blast moisture
Coke ratio
Blast flow rate
(Control variables)
Hot metal temperature
Gas permeability (Furnace pressure loss)
Hot metal production rate
Gas permeability
Hot metal temperature
Hot metal production rate

FIG. 2

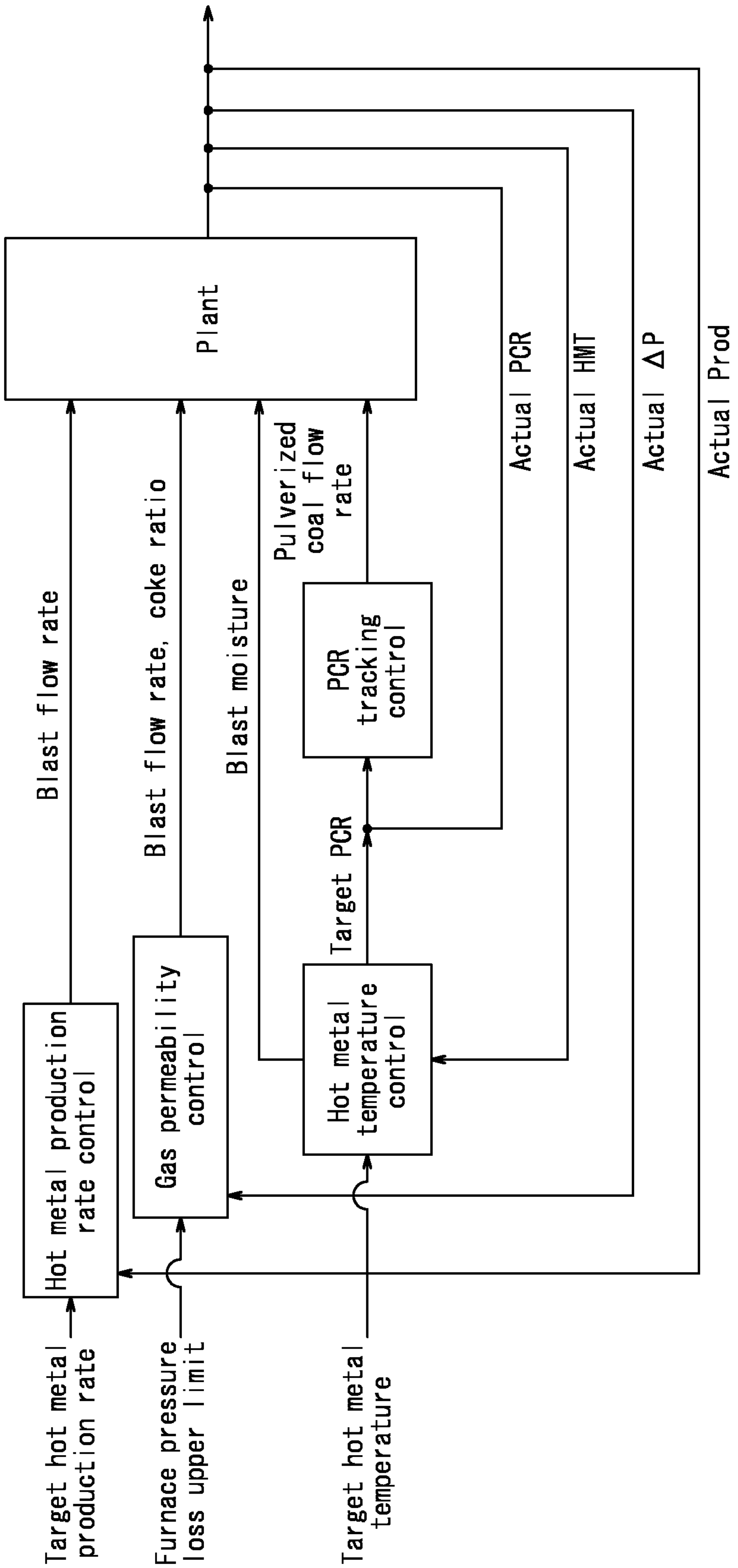

Plant
Blast flow rate
Blast flow rate, coke ratio
Blast moisture
Pulverized coal flow rate
PCR tracking control
Target PCR
Actual PCR
Actual HMT
Actual ΔP
Actual Prod
Hot metal production rate control
Gas permeability control
Hot metal temperature control
Target hot metal production rate
Furnace pressure loss upper limit
Target hot metal temperature

FIG. 3

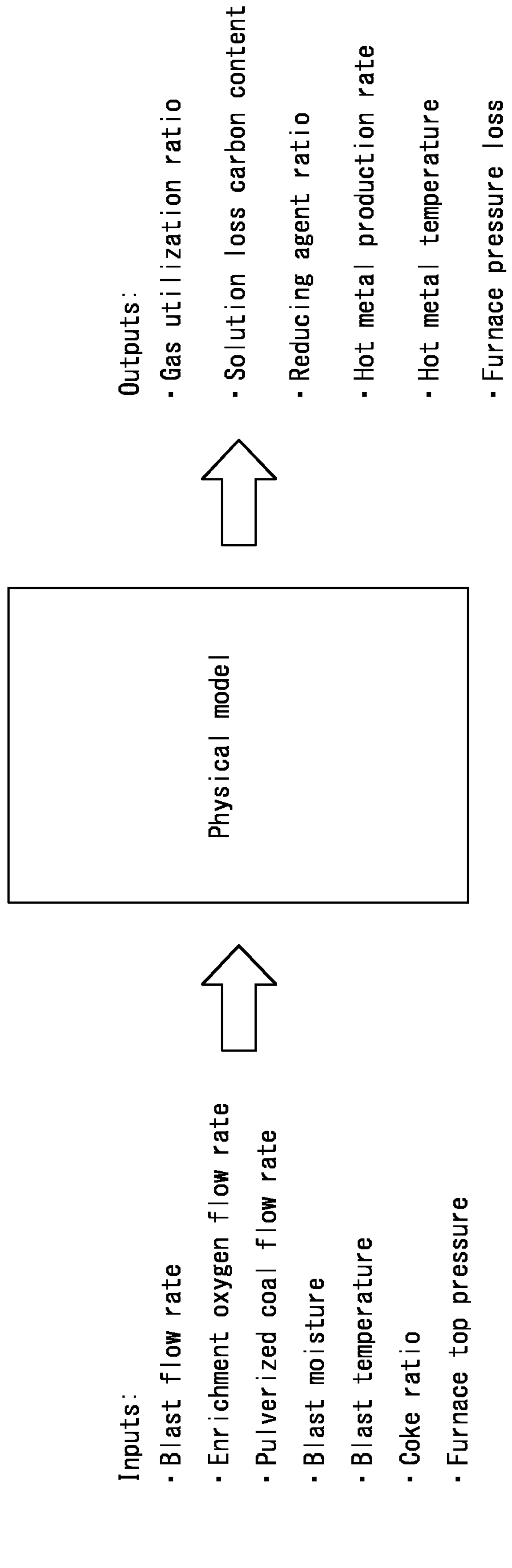

Inputs:
· Blast flow rate
· Enrichment oxygen flow rate
· Pulverized coal flow rate
· Blast moisture
· Blast temperature
· Coke ratio
· Furnace top pressure
Physical model
Outputs:
· Gas utilization ratio
· Solution loss carbon content
· Reducing agent ratio
· Hot metal production rate
· Hot metal temperature
· Furnace pressure loss

FIG. 4

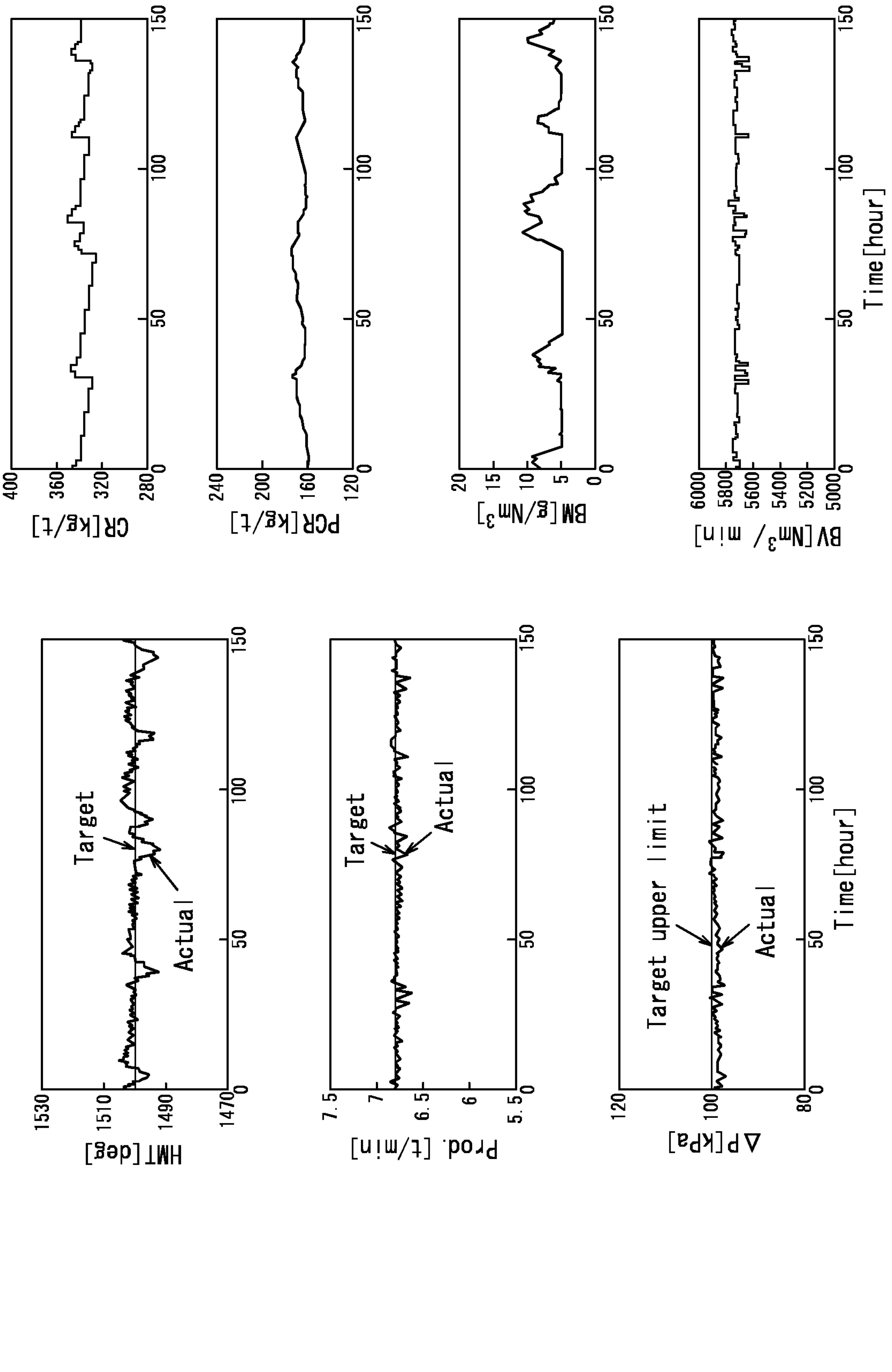

HMT[deg]
Target
Actual
Prod. [t/min]
Target
Actual
ΔP[kPa]
Target upper limit
Actual
Time[hour]
CR[kg/t]
PCR[kg/t]
BM[g/Nm3]
BV[Nm3/min]
Time[hour]

FIG. 5

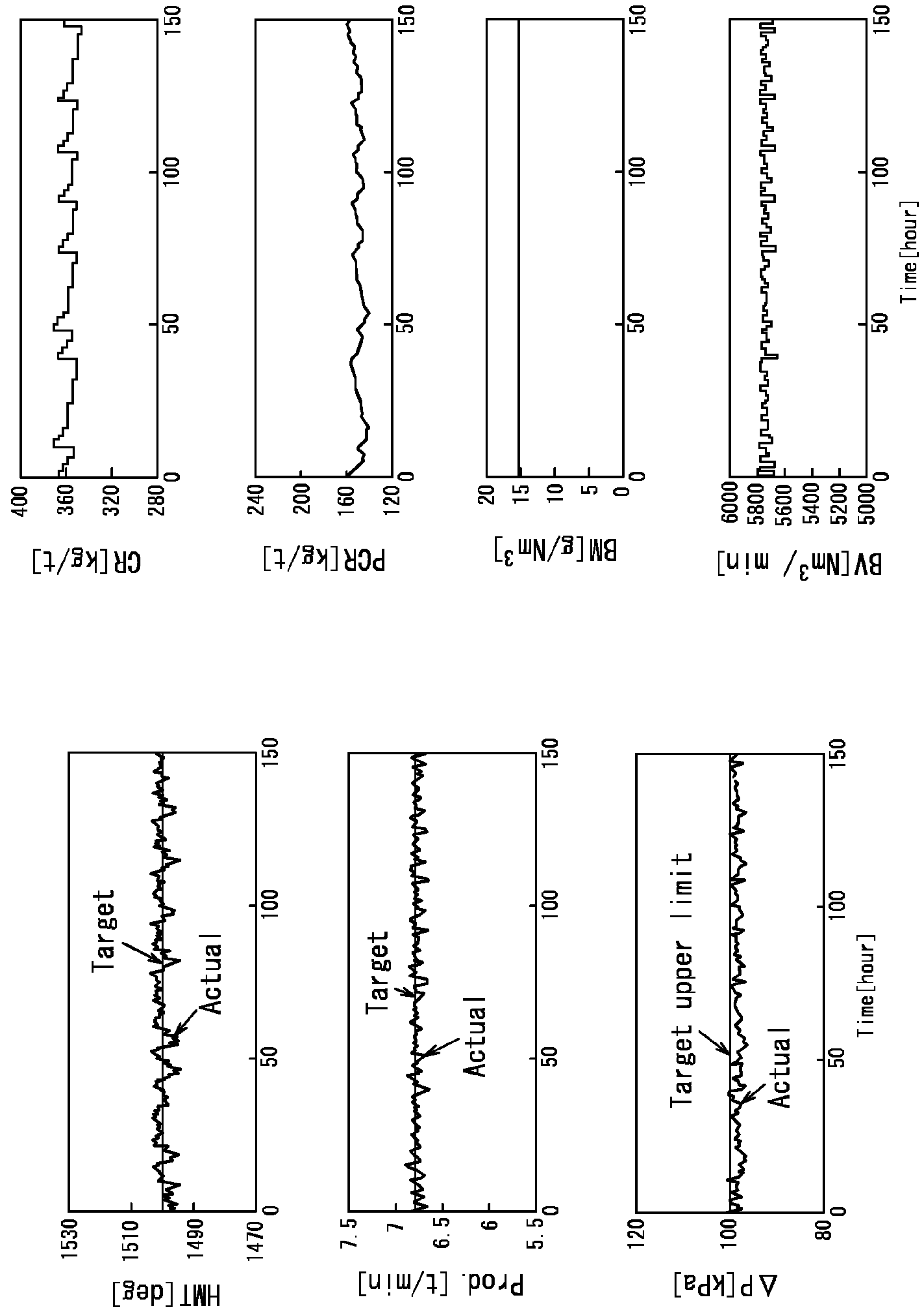

CR[kg/t]
PCR[kg/t]
BM[g/Nm3]
BV[Nm3/ min]
Time[hour]
HMT[deg]
Target
Actual
Prod. [t/min]
Target
Actual
ΔP[kPa]
Target upper limit
Actual
Time[hour]

FIG. 6

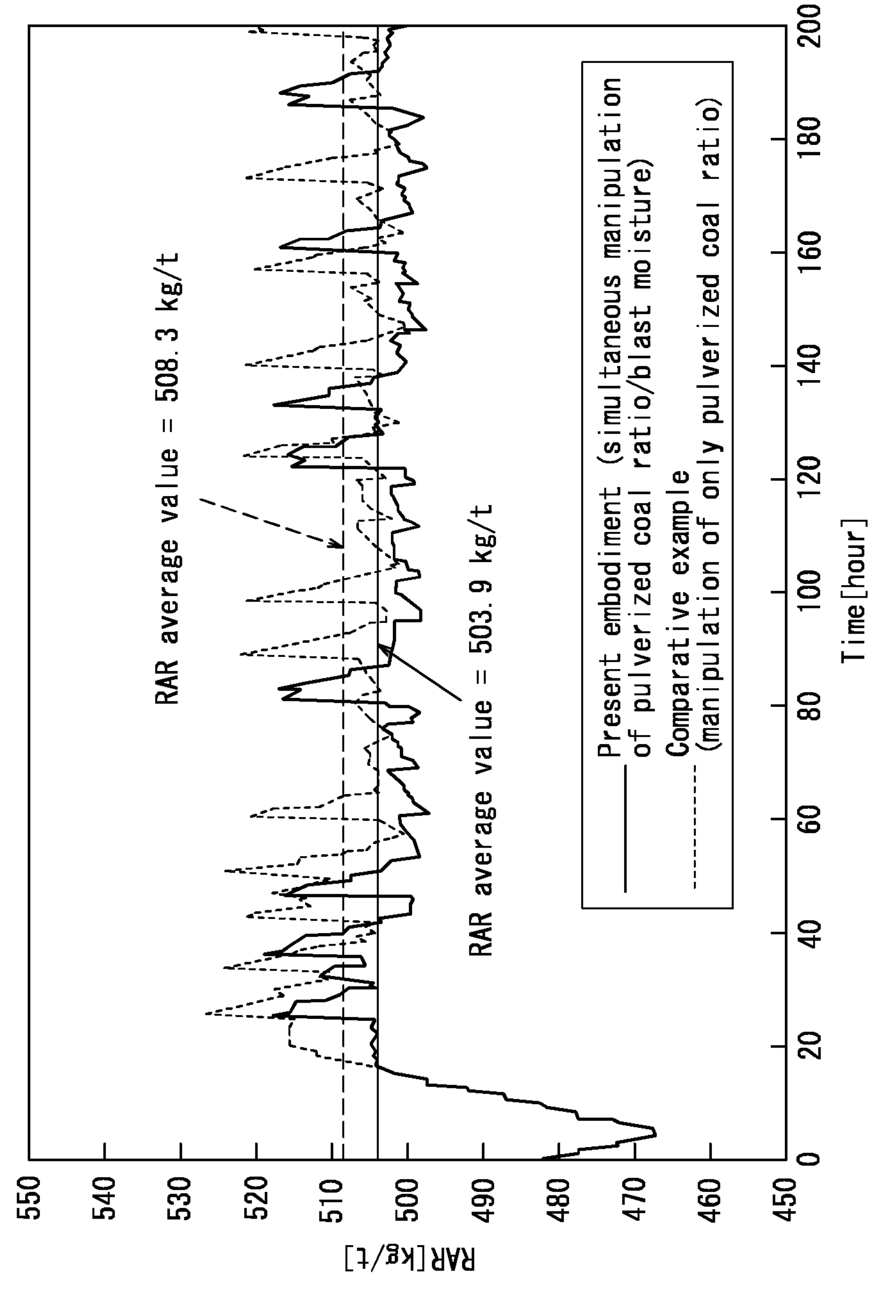
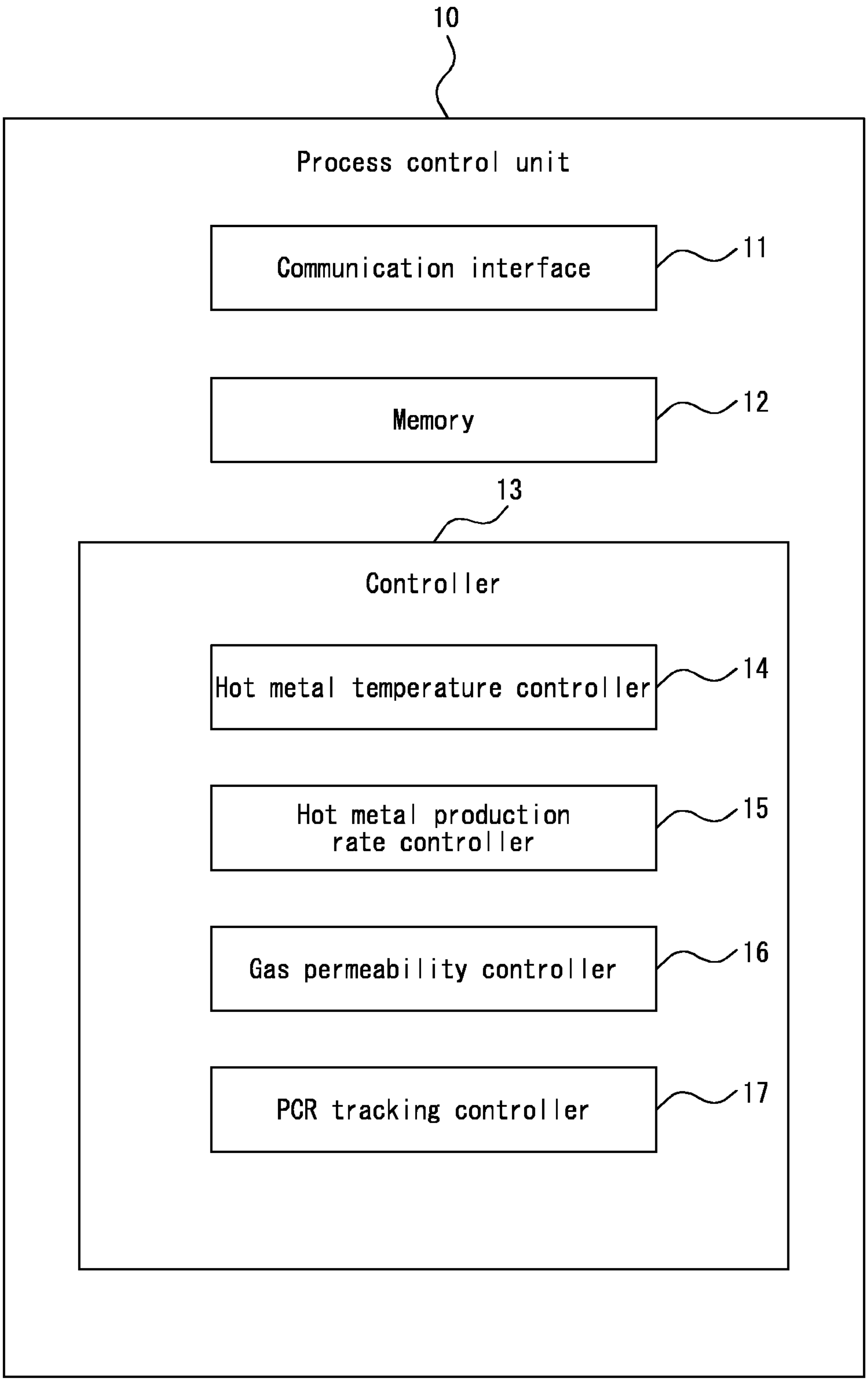

RAR average value = 508.3 kg/t
RAR average value = 503.9 kg/t
Present embodiment (simultaneous manipulation of pulverized coal ratio/blast moisture)
Comparative example (manipulation of only pulverized coal ratio)
RAR[kg/t]
Time[hour]
550
540
530
520
510
500
490
480
470
460
450
0
20
40
60
80
100
120
140
160
180
200

FIG. 7


10
Process control unit
Communication interface
11
Memory
12
13
Controller
Hot metal temperature controller
14
Hot metal production rate controller
15
Gas permeability controller
16
PCR tracking controller
17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2023/028830

A. CLASSIFICATION OF SUBJECT MATTER

C21B 5/00(2006.01)i
FI: C21B5/00 316; C21B5/00 319

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

C21B5/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2023
Registered utility model specifications of Japan 1996-2023
Published registered utility model applications of Japan 1994-2023

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	JP 2000-129319 A (KAWASAKI SEITETSU K.K.) 09 May 2000 (2000-05-09) paragraphs [0001]-[0092], fig. 1-5	1-2, 4-7 3
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Y	JP 06-172825 A (NIPPON STEEL CORP.) 21 June 1994 (1994-06-21) paragraphs [0001]-[0007]	1-2, 4-7
Y	JP 2022-014169 A (JFE STEEL CORP.) 19 January 2022 (2022-01-19) paragraph [0002]	1-2, 4-7
Y	JP 2012-087375 A (JFE STEEL CORP.) 10 May 2012 (2012-05-10) paragraphs [0001]-[0031]	1-2, 4-7

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
06 September 2023	**19 September 2023**
Name and mailing address of the ISA/JP **Japan Patent Office (ISA/JP)** **3-4-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8915** **Japan**	Authorized officer Telephone No.

Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2023/028830

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WO 2015/105107 A1	16 July 2015	US 2016/0326604 A1 paragraph [0002] EP 3093352 A1 CA 2935522 A1 KR 10-2016-0105476 A CN 105899686 A CN 113999945 A	
JP 2002-146414 A	22 May 2002	(Family: none)	
JP 06-172825 A	21 June 1994	(Family: none)	
JP 2022-014169 A	19 January 2022	EP 4177359 A1 paragraph [0002] CN 115735010 A KR 10-2023-0019154 A	
JP 2012-087375 A	10 May 2012	(Family: none)	

Form PCT/ISA/210 (patent family annex) (January 2015)

REFERENCES CITED IN THE DESCRIPTION

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- **MICHIHARU HATANO et al.** Investigation of Blow-in Operation through the Blast Furnace Dynamic Model. *Tetsu-to-Hagane*, vol. 68, 2369 **[0020]**
- **Y. HASHIMOTO**. Online prediction of hot metal temperature using transient model and moving horizon estimation. *ISIJ Int.*, 2019, vol. 59, 1534 **[0028]**