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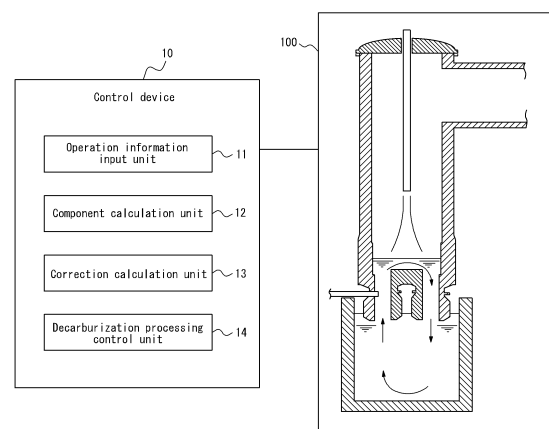
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(54) **CONTROL DEVICE FOR VACUUM DEGASSING EQUIPMENT, CONTROL METHOD FOR VACUUM DEGASSING EQUIPMENT, OPERATION METHOD, AND MANUFACTURING METHOD FOR MOLTEN STEEL**

(57) A control device (10) for a vacuum degassing line includes an operation information input unit (11) configured to receive information regarding a weight and concentrations of components of the molten steel before the decarburization processing, track records of operation when the decarburization processing is being executed, and information regarding auxiliary raw materials; a component calculation unit (12) configured to estimate an in-molten-steel carbon concentration in the molten steel; a correction calculation unit (13) configured to calculate correction parameters to correct an estimated value of carbon content discharged from the vacuum degassing line and the estimated in-molten-steel carbon concentration in the molten steel; and a decarburization processing control unit (14) configured to end the decarburization processing when the in-molten-steel carbon concentration in the molten steel that has been corrected by the correction parameter reaches a target value.

FIG. 1



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Description

TECHNICAL FIELD

[0001] The present disclosure relates to a control device for a vacuum degassing line, a control method for a vacuum degassing line, an operation method, and a method of producing molten steel.

BACKGROUND

[0002] In steelmaking processes, components of molten steel are adjusted, by removing impurities, including carbon, in hot metal and adding useful alloy components. For carbon in particular, it is possible to accelerate decarburization by placing the molten steel under a vacuum environment using a vacuum degassing line, so as to produce ultra-low carbon steel with a carbon concentration in the molten steel of less than 10 ppm.

[0003] Here, in vacuum degassing processing, the carbon concentration in the molten steel is not directly measured but only indirectly estimated from concentrations of carbon monoxide and carbon dioxide in exhaust gas. In the production of ultra-low carbon steel, operators tend to perform excessively long decarburization processing because of concerns about out-of-standard carbon concentrations.

[0004] To solve the problem of prolonged processing time due to excessive decarburization processing, a highly accurate estimation of the carbon concentration in molten steel during the processing is effective, and various methods have been proposed. Methods of estimating the carbon concentration in molten steel can be broadly classified into two categories. One method is to physically study details of decarburization reaction in a vacuum degassing line and build a decarburization reaction model (for example, Non-Patent Literature [NPL] 1). The other method is to estimate the carbon concentration in molten steel, by calculating the amount of decarburization from a flow rate and a measured value (for example, measured values of concentrations of components) of exhaust gas discharged from a vacuum degassing line during processing. As a combination of both, a method of determining parameters of a decarburization reaction model from a measured value of exhaust gas and estimating the carbon concentration in molten steel using the decarburization reaction model with the determined parameters has also been proposed (for example, Patent Literature [PTL] 1 and Patent Literature [PTL] 2).

[0005] In another example, Patent Literature (PTL) 3 also describes a method of correcting an estimated value of carbon concentration in molten steel using the difference between a decarburization rate calculated from a decarburization reaction model based on the observer theory and a decarburization rate calculated from a measurement value of exhaust gas.

CITATION LIST

Patent Literatures

[0006]

PTL 1: JP 2005-330512 A
PTL 2: JP 2015-101742 A
PTL 3: JP 2006-104521 A

Non-Patent Literatures

[0007]

NPL 1: Shinya Kitamura et al., "Decarburization Model for Vacuum Degasser," Iron and Steel, vol. 80 (1994), no. 3, pp. 213-218.
NPL 2: Yoshihiko Higuchi et al., "Effects of [C], [O] and Pressure on RH Vacuum Decarburization," Iron and Steel, vol. 84 (1998), no. 10, pp. 709-714.

SUMMARY

(Technical Problem)

[0008] In a case in which a decarburization reaction model is built from physical studies, it is often difficult to determine model parameters when trying to represent details of decarburization reaction. For example, the decarburization reaction

model proposed in NPL 1 introduces an additional pressure parameter to formulate CO bubble formation inside molten steel, but this value is determined from results of basic experiments. As is pointed out in NPL 2, there is no verification that the same additional pressure parameter value is safe to use in an actual vacuum degassing line. Besides, it is assumed that model parameters for vacuum degassing lines vary due to the different equipment shapes and operating conditions. For the above reasons, even in a case in which the decarburization reaction model proposed in NPL 1 is introduced, a highly accurate estimation of carbon concentration in molten steel cannot be achieved when the equipment shapes or operating conditions are different.

[0009] As described above, the technology of PTL 1 and PTL 2 determine parameters of a decarburization reaction model from a measured value of exhaust gas that reflects track records of decarburization, so that model parameters suitable for, for example, equipment shapes and operating conditions can be set. However, because errors in the measured value of exhaust gas are directly reflected in the model parameters, there is a need for a method of further improving the accuracy of estimated value of carbon concentration in molten steel.

[0010] As described above, the technology of PTL 3 corrects an estimated value of carbon concentration in molten steel based on the difference between a decarburization rate calculated from the decarburization reaction model and a decarburization rate calculated from a measured value of exhaust gas, but it assumes that the decarburization reaction model is accurate. Accordingly, because errors in the decarburization reaction model are reflected in an estimation result, there is a need for a method of further improving the accuracy of estimated value of carbon concentration in molten steel.

[0011] Thus, according to the conventional technology, where there can be errors in a decarburization reaction model and errors in a measured value of exhaust gas, calculation is performed based on the assumption that at least one of the above is accurate. Because the conventional technology estimates a carbon concentration in molten steel by ignoring either errors, the accuracy of estimating the carbon concentration in molten steel is inadequate.

[0012] It would be helpful to provide a control device for a vacuum degassing line, a control method for a vacuum degassing line, an operation method, and a method of producing molten steel by which a carbon concentration in molten steel is highly accurately estimated and decarburization processing is ended at an appropriate timing.

(Solution to Problem)

[0013]

(1) A control device for a vacuum degassing line according to an embodiment of the present disclosure is a control device for a vacuum degassing line that controls operations of the vacuum degassing line that performs decarburization processing by placing molten steel under a reduced pressure environment, the control device including:

an operation information input unit configured to receive information regarding a weight and concentrations of components of the molten steel before the decarburization processing, track records of operation including measurement results of flow rate and concentrations of components of exhaust gas discharged from the vacuum degassing line when the decarburization processing is being executed, and information regarding auxiliary raw materials charged when the decarburization processing is being executed;

a component calculation unit configured to estimate an in-molten-steel carbon concentration in the molten steel, based on the information regarding the weight and the concentrations of components of the molten steel before the decarburization processing and the track records of operation;

a correction calculation unit configured to calculate correction parameters to correct an estimated value of carbon content discharged from the vacuum degassing line and the estimated in-molten-steel carbon concentration in the molten steel, based on the estimated in-molten-steel carbon concentration in the molten steel, the measurement results of flow rate and concentrations of components of exhaust gas, and a result of carbon balance calculation; and

a decarburization processing control unit configured to end the decarburization processing when the in-molten-steel carbon concentration in the molten steel that has been corrected by the correction parameter reaches a target value.

(2) As an embodiment of the present disclosure, in (1), the correction calculation unit calculates the correction parameters in accordance with an evaluation function based on a difference between an amount of decrease in carbon content in the molten steel and a carbon content in exhaust gas.

(3) As an embodiment of the present disclosure, in (2), the evaluation function includes a term based on a squared value calculated by subtracting the carbon content in the exhaust gas from a carbon content in the molten steel and a carbon content in the auxiliary raw materials, and a term

based on a squared value of a difference between a carbon content in exhaust gas per unit time and a decarburization rate.

(4) As an embodiment of the present disclosure, in (2) or (3),

the evaluation function includes the correction parameter for a measured value of exhaust gas that is set as a correction coefficient to be multiplied by a value before correction.

(5) A control method for a vacuum degassing line according to an embodiment of the present disclosure is

a control method for a vacuum degassing line configured to be executed by a control device for the vacuum degassing line that controls operations of the vacuum degassing line that performs decarburization processing by placing molten steel under a reduced pressure environment, the control method including:

an input step of receiving information regarding a weight and concentrations of components of the molten steel before the decarburization processing, track records of operation including measurement results of flow rate and concentrations of components of exhaust gas discharged from the vacuum degassing line when the decarburization processing is being executed, and information regarding auxiliary raw materials charged when the decarburization processing is being executed;

a component calculation step of estimating an in-molten-steel carbon concentration in the molten steel, based on the information regarding the weight and the concentrations of components of the molten steel before the decarburization processing and the track records of operation;

a correction calculation step of calculating correction parameters to correct an estimated value of carbon content discharged from the vacuum degassing line and the estimated in-molten-steel carbon concentration in the molten steel, based on the estimated in-molten-steel carbon concentration in the molten steel, the measurement results of flow rate and concentrations of components of exhaust gas, and a result of carbon balance calculation; and a decarburization processing end step of ending the decarburization processing when the in-molten-steel carbon concentration in the molten steel that has been corrected by the correction parameter reaches a target value.

(6) As an embodiment of the present disclosure, in (5),

the correction calculation step calculates the correction parameters in accordance with an evaluation function based on a difference between an amount of decrease in carbon content in the molten steel and a carbon content in exhaust gas.

(7) As an embodiment of the present disclosure, in (6),

the evaluation function includes a term based on a squared value calculated by subtracting the carbon content in the exhaust gas from a carbon content in the molten steel and a carbon content in the auxiliary raw materials, and a term based on a squared value of a difference between a carbon content in exhaust gas per unit time and a decarburization rate.

(8) As an embodiment of the present disclosure, in (6) or (7),

the evaluation function includes the correction parameter for a measured value of exhaust gas that is set as a correction coefficient to be multiplied by a value before correction.

(9) An operation method according to an embodiment of the present disclosure includes

operating a vacuum degassing line, by executing the control method according to any one of (5) to (7).

(10) A method of producing molten steel according to an embodiment of the present disclosure includes

producing refined molten steel, by refining molten steel in a vacuum degassing line that is operated by the operation method according to (9).

(Advantageous Effect)

[0014] According to the method of the present disclosure, errors contained in a decarburization reaction model, a measured value of exhaust gas, and a carbon content of in the exhaust gas calculated from these can be corrected at the same time. Accordingly, there are provided the control device for a vacuum degassing line, the control method for a vacuum degassing line, the operation method, and the method of producing molten steel by which an in-molten-steel carbon concentration can be highly accurately estimated, decarburization processing can be ended at an appropriate timing for carbon concentration standards, and decarburization processing time can be reduced.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] In the accompanying drawings:

FIG. 1 is a block diagram illustrating a configuration of a control device for a vacuum degassing line according to an embodiment of the present disclosure;

FIG. 2 is a flowchart illustrating flow of decarburization control processing according to an embodiment of the present disclosure;

FIG. 3 illustrates time-series calculation results of a correction coefficient α for carbon content in exhaust gas, which is a correction parameter in examples of the present disclosure; and

FIG. 4 illustrates time-series calculation results of a correction value for in-molten-steel carbon concentration in a vacuum vessel, ΔC_V , which is a correction parameter in the examples of the present disclosure.

DETAILED DESCRIPTION

[0016] Hereinafter, a control device and a control method for a vacuum degassing line according to an embodiment of the present disclosure will be described with reference to the drawings. In the present embodiment, the vacuum degassing line is described as an RH vacuum degassing line, but it is not limited to the RH vacuum degassing line. The control method described below can also be implemented for a line (equipment) that includes a vacuum vessel and a single immersion tube to be immersed in a ladle and sucked up into the molten steel vacuum vessel, or a line (equipment) that does not include a vacuum vessel and brings a molten steel surface in the ladle to a vacuum state.

[Configuration]

[0017] FIG. 1 is a block diagram illustrating a configuration of a control device 10 according to an embodiment of the present disclosure. The control device 10 is a control device 10 for a vacuum degassing line 100 and controls operations of the vacuum degassing line 100. In the vacuum degassing line 100, decarburization processing is performed by placing at least molten steel under a reduced pressure environment. In the present embodiment, the vacuum degassing line 100 is operated by the control device 10 executing a later-described control method for the vacuum degassing line 100. That is, the control of the vacuum degassing line 100 is executed as an operation method of the vacuum degassing line 100. Additionally, in the present embodiment, the vacuum degassing line 100 constitutes part of a molten steel production facility. A method of producing molten steel is executed in the molten steel production facility, and the method of producing molten steel includes producing refined molten steel, by refining molten steel in the vacuum degassing line 100.

[0018] As illustrated in FIG. 1, the control device 10 includes an operation information input unit 11, a component calculation unit 12, a correction calculation unit 13, and a decarburization processing control unit 14.

[0019] The operation information input unit 11 acquires information about operation using the vacuum degassing line 100. In the present embodiment, the operation information input unit 11 receives information regarding a weight and concentrations of components of molten steel before decarburization processing, track records of operation including measurement results of flow rate and concentrations of components of exhaust gas discharged from the vacuum degassing line 100 when the decarburization processing is being executed, and information regarding auxiliary raw materials charged when the decarburization processing is being executed.

[0020] The component calculation unit 12 estimates an in-molten-steel carbon concentration in the molten steel, based on operation information acquired by the operation information input unit 11. In the present embodiment, the component calculation unit 12 estimates the in-molten-steel carbon concentration in the molten steel, based on the information regarding the weight and the concentrations of components of the molten steel before the decarburization processing and the track records of operation.

[0021] The correction calculation unit 13 calculates correction parameters to correct an estimated value of carbon content discharged from the vacuum degassing line 100 and the estimated in-molten-steel carbon concentration in the molten steel. In the present embodiment, the correction calculation unit 13 calculates the correction parameters to correct the estimated value of carbon content discharged from the vacuum degassing line 100 and the estimated in-molten-steel carbon concentration in the molten steel, based on the estimated in-molten-steel carbon concentration in the molten steel, the measurement results of flow rate and concentrations of components of exhaust gas, and a result of carbon balance calculation.

[0022] The decarburization processing control unit 14 ends the decarburization processing when the in-molten-steel carbon concentration that has been corrected by the correction parameter reaches a target value.

[0023] The control device 10 is composed, for example, of an information processing device, such as a computer. The control device 10 may be configured to function as the operation information input unit 11, the component calculation unit 12, the correction calculation unit 13, and the decarburization processing control unit 14 by having an arithmetic processing unit, such as a CPU (Central Processing Unit), of the information processing device execute a program.

[0024] The vacuum degassing line 100 may be of any known configuration. As described above, an RH vacuum degassing line is used in the present embodiment. The RH vacuum degassing line includes, for example, a vacuum vessel and a ladle, with two immersion tubes connecting them. The vacuum vessel is connected to an exhaust duct, through which gas inside the vacuum vessel is discharged, so as to depressurize the vacuum vessel and suck up molten steel in the ladle. The molten steel is then circulated between the vacuum vessel and the ladle, by blowing inert gas through the immersion

tubes from their one ends. Oxygen may also be blown from a blowing lance installed in the vacuum vessel for the purpose of accelerating the decarburization processing.

[0025] The control device 10 with the above configuration highly accurately estimates an in-molten-steel carbon concentration, by executing decarburization control processing that will be described below. The highly accurate estimation can avoid excessively long decarburization processing due to concerns about out-of-standard carbon concentrations, resulting in a reduction in decarburization processing time. The flow of the decarburization control processing according to an embodiment of the present disclosure will be described below with reference to FIG. 2.

[Decarburization Control Processing]

[0026] FIG. 2 is a flowchart illustrating flow of decarburization control processing executed by the control device 10. The flowchart of FIG. 2 starts at a time when instructions to execute the decarburization processing is input, and processing of Step S1 is performed.

[0027] In the processing of Step S1, the operation information input unit 11 acquires a weight of molten steel measured before the start of decarburization processing and concentrations of components obtained by component analysis. Examples of the components for which the concentrations are to be measured include C, Si, Mn, P, S, Al, Cu, Nb, and Ti. If necessary for calculation in the composition calculation unit 12, the operation information input unit 11 may also acquire a measurement result of molten steel temperature. In the example of FIG. 2, the temperature is also acquired. This completes the processing of Step S1, and the decarburization control processing proceeds to processing of Step S2.

[0028] In the processing of Step S2, the operation information input unit 11 acquires track records of operation during the decarburization processing. The track records of operation are acquired for items necessary for calculation in the component calculation unit 12 and the correction calculation unit 13. In the present embodiment, the operation information input unit 11 acquires measurement results of flow rate and concentrations of components of exhaust gas discharged from the vacuum degassing line 100 as the track records of operation. In the present embodiment, the operation information input unit 11 also acquires information regarding auxiliary raw materials charged when the decarburization processing is being executed. Concrete examples of the information regarding auxiliary raw materials include types and charge amounts of the auxiliary raw materials. In addition, information, such as pressure of the vacuum vessel, flow rate of inert gas to be circulated, or oxygen flow rate from a top-blowing lance during the decarburization processing, may be input to the operation information input unit 11. In a case in which the processing of Step S2 is executed after Step S6, which will be described later, the operation information input unit 11 may also acquires estimated values of molten steel components, including an estimated value of in-molten-steel carbon concentration. This completes the processing of Step S2, and the decarburization control processing proceeds to processing of Step S3 and Step S4. Here, Steps S1 and Step S2 correspond to an input step.

[0029] In the processing of Step S3, the component calculation unit 12 calculates (estimates) an in-molten-steel carbon concentration according to a predetermined decarburization reaction model. In the present embodiment, the composition calculation unit 12 acquires input information, such as track records of operation, every predetermined period or continuously, and estimates the in-molten-steel carbon concentration in the molten steel every predetermined period or continuously. There are two requirements of the decarburization reaction model used by the component calculation unit 12. One is that it is capable of estimating an in-molten-steel carbon concentration every predetermined period or continuously, and the other is that the decarburization rate, namely, the rate of change in in-molten-steel carbon concentration, is expressed as a function of in-molten-steel carbon concentration in an area in which decarburization reaction occurs. The area in which the decarburization reaction occurs corresponds to the vacuum vessel in the RH vacuum degassing line. These two requirements are conditions that general decarburization reaction models obviously satisfy.

[0030] In the present embodiment, a decarburization reaction model according to the following Formula (1) and Formula (2) is used, while it is assumed that each of a molten steel concentration in the vacuum vessel and that in the ladle is in a fully mixed state during the decarburization processing in the RH vacuum degassing line.

[Math. 1]

$$w_L \frac{dC_L}{dt} = Q(C_V - C_L) \dots \text{Formula (1)}$$

$$w_V \frac{dC_V}{dt} = Q(C_L - C_V) - \sum_i a k_i(C_V)(C_V - C_{E,i}) + C_{alloy} \dots \text{Formula (2)}$$

[0031] Here, w [kg] is molten steel mass. C [ppm] is in-molten-steel carbon concentration. Q [kg/s] is molten steel

circulation rate. a_k [kg/s] is decarburization reaction capacity coefficient. C_E [ppm] is equilibrium value of in-molten-steel carbon concentration in the vacuum vessel. C_{alloy} [ppm] is carbon weight in charged auxiliary raw materials in terms of in-molten-steel carbon concentration. Formula (2) explicitly indicates that the decarburization reaction capacity coefficient depends on the carbon concentration in the molten steel in the vacuum vessel. The subscript L indicates that it is a physical quantity of molten steel in the ladle. The subscript V indicates that it is a physical quantity of molten steel in the vacuum vessel. For example, C_V [ppm] indicates in-molten-steel carbon concentration in the vacuum vessel. The subscript i is used to identify a specific decarburization reaction site. Concrete examples of the decarburization reaction site may include a molten steel surface and inert gas bubbles for circulation.

[0032] A carbon content discharged as exhaust gas is calculated by the second term of Formula (2). The amount of change in in-molten-steel carbon concentration per very short period of time can also be calculated from Formula (1) and Formula (2) and subtracted from the current in-molten-steel carbon concentration, to thereby calculate an in-molten-steel carbon concentration after the very short period of time. This completes the processing of Step S3. Here, Step S3 corresponds to a component calculation step.

[0033] In the processing of Step S4, the correction calculation unit 13 calculates a carbon content in exhaust gas, based on the measurement results of flow rate and concentrations of components of the exhaust gas. Given that carbon discharged from molten steel takes the form of CO or CO₂, the carbon content in the exhaust gas per unit time is represented by the following Formula (3). A cumulative amount of carbon discharged from the start of the processing (time 0) to time t is also represented by the following Formula (4).

[Math. 2]

$$q_{C,OG}(t) = m_C \frac{V_{\text{off}}(t)}{22.4} \cdot \frac{r_{CO}(t) + r_{CO_2}(t)}{100} \quad \dots \text{Formula (3)}$$

$$Q_{C,OG}(t) = \int_0^t q_{C,OG}(t') dt' \quad \dots \text{Formula (4)}$$

[0034] Here, $q_{C,OG}(t)$ [kg/s] is carbon content in exhaust gas per unit time at time t. m_C [g/mol] is molar mass of carbon. $V_{\text{off}}(t)$ [Nm³/s] is volumetric flow rate of the exhaust gas at time t. $r_{CO}(t)$ [vol%] is CO concentration in the exhaust gas at time t. $r_{CO_2}(t)$ [vol%] is CO₂ concentration in the exhaust gas at time t. $Q_{C,OG}(t)$ [kg] is cumulative amount of carbon discharged from time 0 to time t.

[0035] Here, in a case in which measurement results of flow rate and concentrations of components of exhaust gas contain known errors, it is preferable for the correction calculation unit 13 to remove or reduce the known errors before executing the calculation of Formula (3). For example, in a case in which a measured value of CO concentration and a measured value of CO₂ concentration take a non-zero value even at times when no measurements are being made (in a case in which the zero points are shifted), the measured values minus the amount of zero point shift may be used in the calculation. This completes the processing of Step S4. Once Steps S3 and Step S4 are completed, the decarburization control processing proceeds to processing of Step S5. Here, the processing of Step S4 can be executed independently from the processing of Step S3, and Steps S3 and Step S4 may be executed in parallel, as in the present embodiment. However, the present disclosure is not limited to parallel processing, and Steps S3 and Step S4 may be executed in sequence, and which comes first (execution order) can also be determined without any limitations in this case.

[0036] Here, from the law of conservation of mass, the sum of a carbon content in molten steel and a cumulative amount of carbon discharged from the molten steel is equal to the sum of a carbon content in the molten steel before the decarburization processing and a carbon content contained in the auxiliary raw materials charged during the processing. In general, however, calculation using the carbon content in the molten steel based on the in-molten-steel carbon concentration estimated in Step S3 and the cumulative amount of discharged carbon estimated in Step S4 do not satisfy the law of conservation of mass. In the present embodiment, the correction calculation unit 13 determines the deviation from the law of conservation of mass as carbon balance calculation and sets a parameter to correct each error, by assuming that this deviation is due to errors in both the decarburization reaction model and the measured value of exhaust gas.

[0037] In the processing of Step S5, the correction calculation unit 13 determines correction parameters for calculation results in the processing of Step S3 and Step S4 so that the law of conservation of mass is satisfied. The correction value for in-molten-steel carbon concentration in the vacuum vessel, ΔC_V [ppm], is a correction parameter for the decarburization reaction model. The correction coefficient for carbon content in exhaust gas, α , is a correction parameter for a measured value of exhaust gas. With these correction parameters, the calculation results in the processing of Step S3 and Step S4 are corrected as follows.

[0038] First, the in-molten-steel carbon concentration in the vacuum vessel is corrected to $C_V + \Delta C_V$, by adding the

correction value for in-molten-steel carbon concentration in the vacuum vessel, ΔC_V . The carbon content in exhaust gas per unit time is corrected to $\alpha q_{C, OG}(t)$, by multiplying the correction coefficient for carbon content in exhaust gas, α . The accumulated amount of discharged carbon is also corrected to $\alpha Q_{C, OG}(t)$, by multiplying the correction coefficient for carbon content in exhaust gas, α . The correction coefficient for carbon content in exhaust gas, α , and the correction value for in-molten-steel carbon concentration in the vacuum vessel, ΔC_V , which are correction parameters, are determined as solutions to the optimization problem represented by the following Formula (5).

[Math. 3]

$$\min_{\alpha, \Delta C_V} \frac{\{(Q_{C, IN} - \alpha Q_{C, OG}) - Q_{C, ST}(\Delta C_V)\}^2}{\sigma_1^2} + \frac{(\alpha q_{C, OG} - deC(\Delta C_V))^2}{\sigma_2^2} + \frac{(\alpha - \alpha_{ave})^2}{\sigma_3^2} + \frac{\Delta C_V^2}{\sigma_4^2} \dots \text{Formula (5)}$$

[0039] Here, $Q_{C, IN}$ [kg] is the sum of the carbon content in the molten steel before the decarburization processing and the carbon content contained in the auxiliary raw materials charged during the processing. $Q_{C, ST}$ [kg] is the carbon content in the molten steel. The difference between $Q_{C, IN}$ and $Q_{C, ST}$ includes the amount of decrease in carbon content in the molten steel. Furthermore, taking the difference from $\alpha Q_{C, OG}(t)$ corresponds to evaluating the difference between the amount of decrease and the carbon content in exhaust gas (accumulated amount of discharged carbon). $deC(\Delta C_V)$ [kg/s] is a decarburization rate calculated from the decarburization reaction model by the component calculation unit 12. α_{ave} is a standard value of α based on track records of operation. $\sigma_1, \sigma_2, \sigma_3$ and σ_4 are weighting coefficients, which are set by a user, for example. $Q_{C, ST}(\Delta C_V)$ is defined by Formula (6). Furthermore, $deC(\Delta C_V)$ is defined by Formula (7).

[Math. 4]

$$Q_{C, ST}(\Delta C_V) = w_L C_L + w_V (C_V + \Delta C_V) \dots \text{Formula (6)}$$

$$deC(\Delta C_V) = \sum_i a k_i (C_V + \Delta C_V) \{(C_V + \Delta C_V) - C_{E, i}\} \dots \text{Formula (7)}$$

[0040] The first term in Formula (5) represents the deviation from the law of conservation of mass for carbon. The first term is zero when the law of conservation of mass is fully satisfied. The second term in Formula (5) represents the deviation between the carbon content in exhaust gas per unit time and the decarburization rate calculated from the decarburization reaction model. The second term is zero when the carbon content in exhaust gas per unit time and the decarburization rate calculated from the decarburization reaction model match. The third term and the fourth term in Formula (5) are to prevent the correction parameters from taking extreme values. First, the correction coefficient for carbon content in exhaust gas, α , is expected to remain approximately the same as the standard value (α_{ave}) in successively performed vacuum degassing processing, because deterioration of an exhaust gas measurement device and degradation of a measurement environment progress over a time scale sufficiently longer than the time required to perform vacuum degassing processing one time. The third term is therefore to add a square value of the difference between α and α_{ave} . The standard value, α_{ave} , can be determined, for example, by calculating an average of correction coefficients for carbon content in exhaust gas, α , for a predetermined number of times of charges that have been processed most recently. The predetermined number of times is preferably a plurality of times and is not limited to a specific value. On the other hand, the error in the decarburization reaction model is expected to be small with respect to the correction value for in-molten-steel carbon concentration in the vacuum vessel, ΔC_V . The fourth term is therefore to add the square value of ΔC_V . In the present embodiment, the correction calculation unit 13 calculates the correction parameters by minimizing Formula (5), which is an evaluation function, but an evaluation function that maximizes it may be used. That is, the correction calculation unit 13 may calculate correction parameters that minimize or maximize the evaluation function.

[0041] Here, the correction coefficient for carbon content in exhaust gas, α , is preferably set as a correction coefficient to be multiplied by a value before correction, unlike the correction value for in-molten-steel carbon concentration in the vacuum vessel, ΔC_V , which is to be added. For example, even when processing is performed so that a carbon content in exhaust gas per unit time is set to $q_{C, OG}(t) + \Delta q_{C, OG}$ using a correction value for carbon content in exhaust gas per unit time, $\Delta q_{C, OG}$ [kg/s], instead of the correction coefficient for carbon content in exhaust gas, α , as a correction parameter for

a measured value of exhaust gas, the accuracy of estimating the carbon concentration cannot be improved. It is known that the range of errors in a measured value of exhaust gas fluctuates significantly over time in decarburization processing. For this reason, in a case in which the correction coefficient for carbon content in exhaust gas, α , is replaced by the correction value ($\Delta q_{C, OG}$) to be added, error removal may be insufficient depending on the timing of progress of decarburization processing to be applied. Besides, it is difficult to vary the correction value in accordance with the timing of progress of decarburization processing. It is therefore preferable that the correction coefficient for carbon content in exhaust gas, α , be set as a correction coefficient to be multiplied by a value before correction, as is the case with the present embodiment.

[0042] Additionally, the evaluation function is not limited to the above Formula (5). For example, the correction coefficient for in-molten-steel carbon concentration in the vacuum vessel, a_V , can be used instead of the correction value for in-molten-steel carbon concentration in the vacuum vessel, ΔC_V . In this case, the in-molten-steel carbon concentration in the vacuum vessel is corrected to $a_V \cdot C_V$, by multiplying the correction coefficient for in-molten-steel carbon concentration in the vacuum vessel, a_V . The correction coefficient for carbon content in exhaust gas, α , and the correction coefficient for in-molten-steel carbon concentration in the vacuum vessel, a_V , which are correction parameters, are then determined as solutions to the optimization problem represented by the following Formula (8).

[Math. 5]

$$\min_{\alpha, \Delta C_V} \frac{\{(Q_{C, IN} - \alpha Q_{C, OG}) - Q_{C, ST}'(a_V)\}^2}{\sigma_1^2} + \frac{(\alpha q_{C, OG} - deC'(a_V))^2}{\sigma_2^2} + \frac{(\alpha - \alpha_{ave})^2}{\sigma_3^2} + \frac{(a_V - 1)^2}{\sigma_4^2} \dots \text{Formula (8)}$$

[0043] When there is no need to correct a value of in-molten-steel carbon concentration estimated by the decarburization reaction model, a_V is 1. The fourth term in Formula (8) is to add the square value of the difference between a_V and 1. $Q_{C, ST}'(a_V)$ is defined by Formula (9). Furthermore, $deC'(a_V)$ is defined by Formula (10).

[Math. 6]

$$Q_{C, ST}'(a_V) = w_L C_L + w_V a_V C_V \dots \text{Formula (9)}$$

$$deC'(a_V) = \sum_i a k_i (a_V C_V) (a_V C_V - C_{E, i}) \dots \text{Formula (10)}$$

[0044] Minimization problems using the evaluation functions of Formula (5) and Formula (8) can be solved using known nonlinear optimization methods. In the following description, it is assumed that the evaluation function of Formula (5) is used. The correction calculation unit 13 determines correction parameters (the correction coefficient for carbon content in exhaust gas, α , and the correction value for in-molten-steel carbon concentration in the vacuum vessel, ΔC_V) by solving the minimization problem of Formula (5). This completes the processing of Step S5, and the decarburization control processing proceeds to processing of Step S6. Here, Step S5 corresponds to a correction calculation step.

[0045] In the processing of Step S6, the in-molten-steel carbon concentration is updated, by adding the correction value for in-molten-steel carbon concentration in the vacuum vessel, ΔC_V , obtained in Step S5 to the estimated value of in-molten-steel carbon concentration obtained in Step S3. This completes the processing of Step S6, and the decarburization control processing proceeds to processing of Step S7.

[0046] In the processing of Step S7, the decarburization processing control unit 14 determines whether the in-molten-steel carbon concentration obtained in Step S6 has reached (or, is less than or equal to) a predetermined target value. When the corrected in-molten-steel carbon concentration is higher than the target value, the processing returns to Step S2 and processing from Step S2 onward is repeated using newly input track records of operation. On the other hand, when the corrected in-molten-steel carbon concentration is less than or equal to the target value, the decarburization processing is ended. Here, Step S7 corresponds to a decarburization processing end step.

[0047] As described above, with the above configuration and processes, the control device 10 for the vacuum degassing line 100, the control method for the vacuum degassing line 100, the operation method, and the method of producing molten steel according to the present embodiment can assume errors in both a decarburization reaction model and a measured value of exhaust gas, and correct these errors at the same time. Thus, there are provided the control device 10 for the vacuum degassing line 100, the control method for the vacuum degassing line 100, the operation method, and the method of producing molten steel by which an in-molten-steel carbon concentration can be highly accurately estimated,

decarburization processing can be ended at an appropriate timing for carbon concentration standards, and decarburization processing time can be reduced.

EXAMPLES

[0048] The advantageous effects of the present disclosure will be concretely described below based on examples, although the present disclosure is not limited to the contents of the examples.

[0049] In the present examples, an RH vacuum degassing line was used to perform decarburization processing, so as to produce ultra-low carbon molten steel wherein an upper specification limit of carbon concentration was 25 ppm. At the end of the decarburization processing, part of the molten steel was taken as a sample, and an in-molten-steel carbon concentration of the sample was measured. The decarburization processing may be ended at the discretion of an operator. The in-molten-steel carbon concentration was estimated by inventive and comparative methods. The inventive method estimated the in-molten-steel carbon concentration as in the embodiment described above. Table 1 presents results of comparison between estimated values at the end of the decarburization processing and actually measured values. Here, the in-molten-steel carbon concentration was estimated by two types of comparative methods. One method was to estimate the carbon concentration by calculating the amount of decarburization from a measured value of exhaust gas (exhaust gas model in Table 1). It is to be noted, however, processing was performed in which α_{ave} , which was an average value of correction coefficients for carbon content in exhaust gas, α , obtained from operational track records of verification charges and charges processed at the same time as these, was multiplied by the amount of decarburization calculated from the measured value of exhaust gas. The other method was to estimate the in-molten-steel carbon concentration using only a decarburization reaction model (decarburization reaction model in Table 1). The latter decarburization reaction model was also used in estimate calculation of in-molten-steel carbon concentration in the inventive method.

[0050] FIG. 3 illustrates changes over time of correction coefficient for carbon content in exhaust gas, α , which is a correction parameter calculated for validation charge A in Table 1. FIG. 4 also illustrates changes over time of correction value for in-molten-steel carbon concentration in the vacuum vessel, ΔC_V , which is a correction parameter calculated for verification charge A in Table 1.

[Table 1]

Verification charge	Actually measured value of carbon concentration [ppm]	Estimated value of carbon concentration [ppm]		
		Comparative method 1 (exhaust gas model)	Comparative method 2 (decarburization reaction model)	Inventive method
A	9	1.72	10.99	9.11
B	10	26.38	8.67	9.21
C	10	22.40	5.87	6.67
D	13	-20.48	14.32	13.66
E	15	-4.35	10.71	11.69

[0051] As presented in Table 1, the inventive method estimates in-molten-steel carbon concentrations closer to the actually measured values than the comparative methods. This has confirmed that the invented method, which assumes errors in both a decarburization reaction model and a measured value of exhaust gas and corrects these errors, is effective in improving the accuracy of estimating an in-molten-steel carbon concentration.

[0052] Although an embodiment of the present disclosure has been described based on the drawings and examples, it is to be noted that various modifications and changes may be easily made by those skilled in the art based on the present disclosure. Accordingly, such modifications and changes 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. An embodiment according to the present disclosure can be implemented as a storage medium in which a program that is executed by a processor included in a device is recorded. It is to be understood that these are included within the scope of present disclosure.

REFERENCE SIGNS LIST

[0053]

5	10	Control device
	11	Operation information input unit
	12	Component calculation unit
	13	Correction calculation unit
	14	Decarburization processing control unit
10	100	Vacuum degassing line

Claims

1. A control device for a vacuum degassing line that controls operations of the vacuum degassing line that performs decarburization processing by placing molten steel under a reduced pressure environment, the control device comprising:
 - an operation information input unit configured to receive information regarding a weight and concentrations of components of the molten steel before the decarburization processing, track records of operation including measurement results of flow rate and concentrations of components of exhaust gas discharged from the vacuum degassing line when the decarburization processing is being executed, and information regarding auxiliary raw materials charged when the decarburization processing is being executed;
 - a component calculation unit configured to estimate an in-molten-steel carbon concentration in the molten steel, based on the information regarding the weight and the concentrations of components of the molten steel before the decarburization processing and the track records of operation;
 - a correction calculation unit configured to calculate correction parameters to correct an estimated value of carbon content discharged from the vacuum degassing line and the estimated in-molten-steel carbon concentration in the molten steel, based on the estimated in-molten-steel carbon concentration in the molten steel, the measurement results of flow rate and concentrations of components of exhaust gas, and a result of carbon balance calculation; and
 - a decarburization processing control unit configured to end the decarburization processing when the in-molten-steel carbon concentration in the molten steel that has been corrected by the correction parameter reaches a target value.
2. The control device according to claim 1, wherein the correction calculation unit calculates the correction parameters in accordance with an evaluation function based on a difference between an amount of decrease in carbon content in the molten steel and a carbon content in exhaust gas.
3. The control device according to claim 2, wherein the evaluation function includes a term based on a squared value calculated by subtracting the carbon content in the exhaust gas from a carbon content in the molten steel and a carbon content in the auxiliary raw materials, and a term based on a squared value of a difference between a carbon content in exhaust gas per unit time and a decarburization rate.
4. The control device according to claim 2 or 3, wherein the evaluation function includes the correction parameter for a measured value of exhaust gas that is set as a correction coefficient to be multiplied by a value before correction.
5. A control method for a vacuum degassing line configured to be executed by a control device for the vacuum degassing line that controls operations of the vacuum degassing line that performs decarburization processing by placing molten steel under a reduced pressure environment, the control method comprising:
 - an input step of receiving information regarding a weight and concentrations of components of the molten steel before the decarburization processing, track records of operation including measurement results of flow rate and concentrations of components of exhaust gas discharged from the vacuum degassing line when the decarburization processing is being executed, and information regarding auxiliary raw materials charged when the decarburization processing is being executed;
 - a component calculation step of estimating an in-molten-steel carbon concentration in the molten steel, based on the information regarding the weight and the concentrations of components of the molten steel before the decarburization processing and the track records of operation;

a correction calculation step of calculating correction parameters to correct an estimated value of carbon content discharged from the vacuum degassing line and the estimated in-molten-steel carbon concentration in the molten steel, based on the estimated in-molten-steel carbon concentration in the molten steel, the measurement results of flow rate and concentrations of components of exhaust gas, and a result of carbon balance calculation; and a decarburization processing end step of ending the decarburization processing when the in-molten-steel carbon concentration in the molten steel that has been corrected by the correction parameter reaches a target value.

6. The control method according to claim 5, wherein the correction calculation step calculates the correction parameters in accordance with an evaluation function based on a difference between an amount of decrease in carbon content in the molten steel and a carbon content in exhaust gas.
7. The control method according to claim 6, wherein the evaluation function includes a term based on a squared value calculated by subtracting the carbon content in the exhaust gas from a carbon content in the molten steel and a carbon content in the auxiliary raw materials, and a term based on a squared value of a difference between a carbon content in exhaust gas per unit time and a decarburization rate.
8. The control method according to claim 6 or 7, wherein the evaluation function includes the correction parameter for a measured value of exhaust gas that is set as a correction coefficient to be multiplied by a value before correction.
9. An operation method comprising operating a vacuum degassing line, by executing the control method according to any one of claims 5 to 7.
10. A method of producing molten steel comprising producing refined molten steel, by refining molten steel in a vacuum degassing line that is operated by the operation method according to claim 9.

FIG. 1

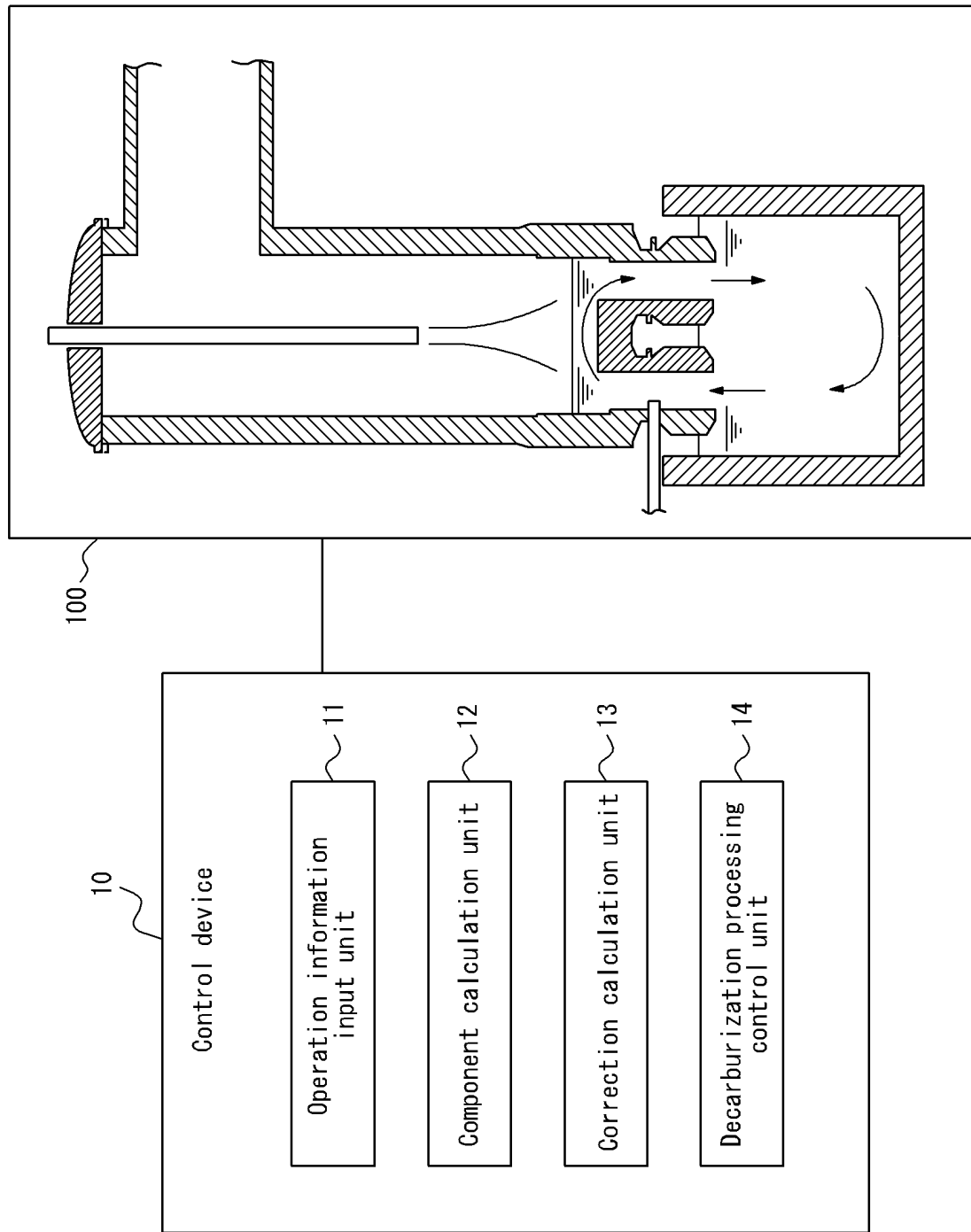


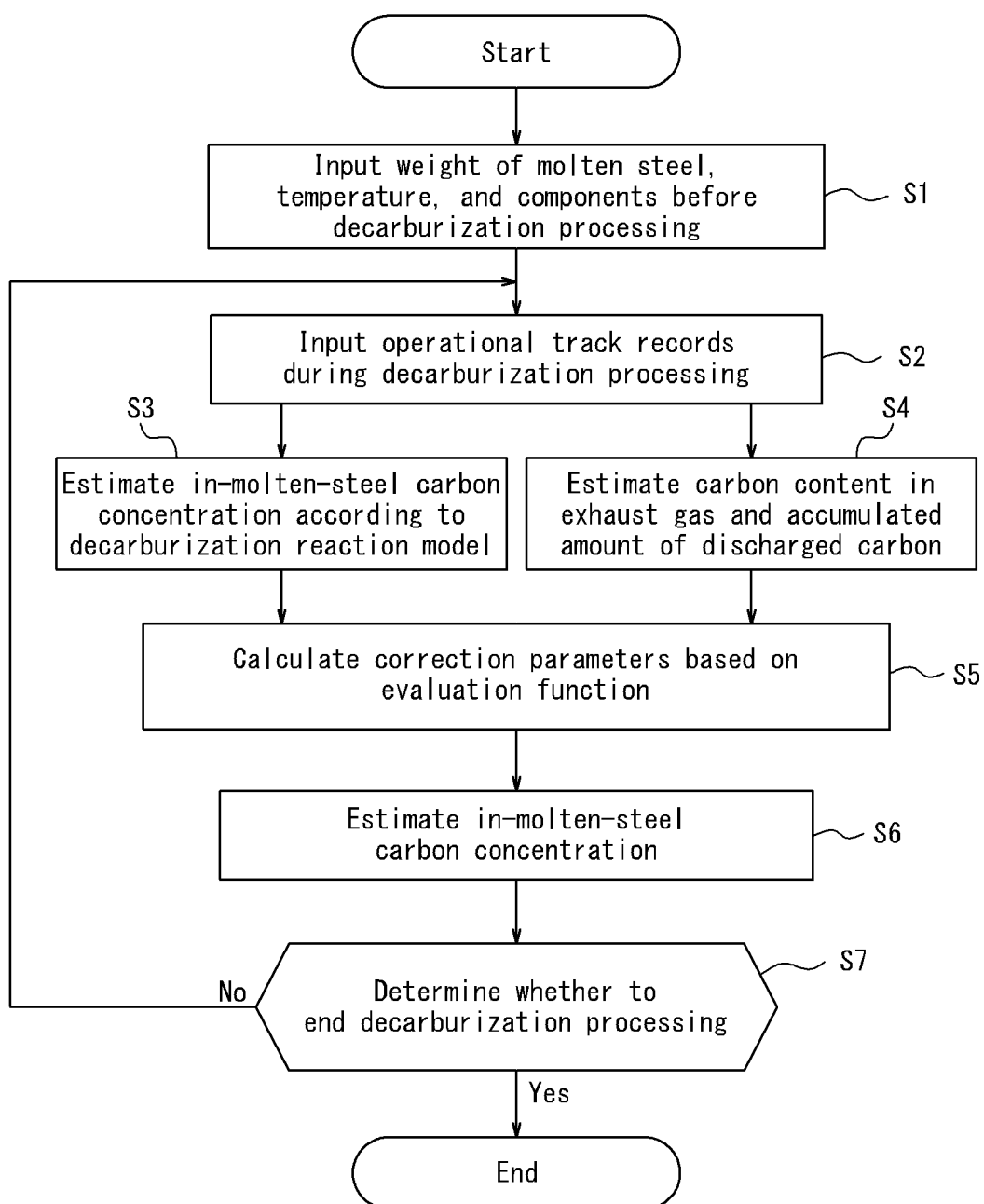
FIG. 2

FIG. 3

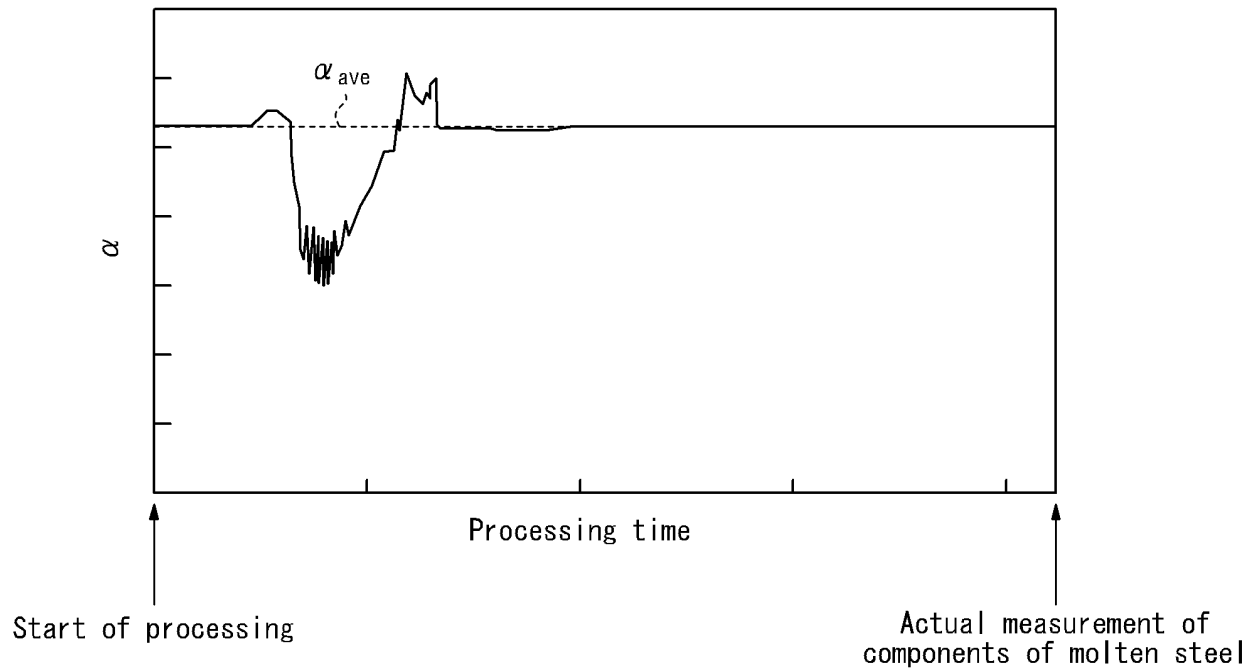
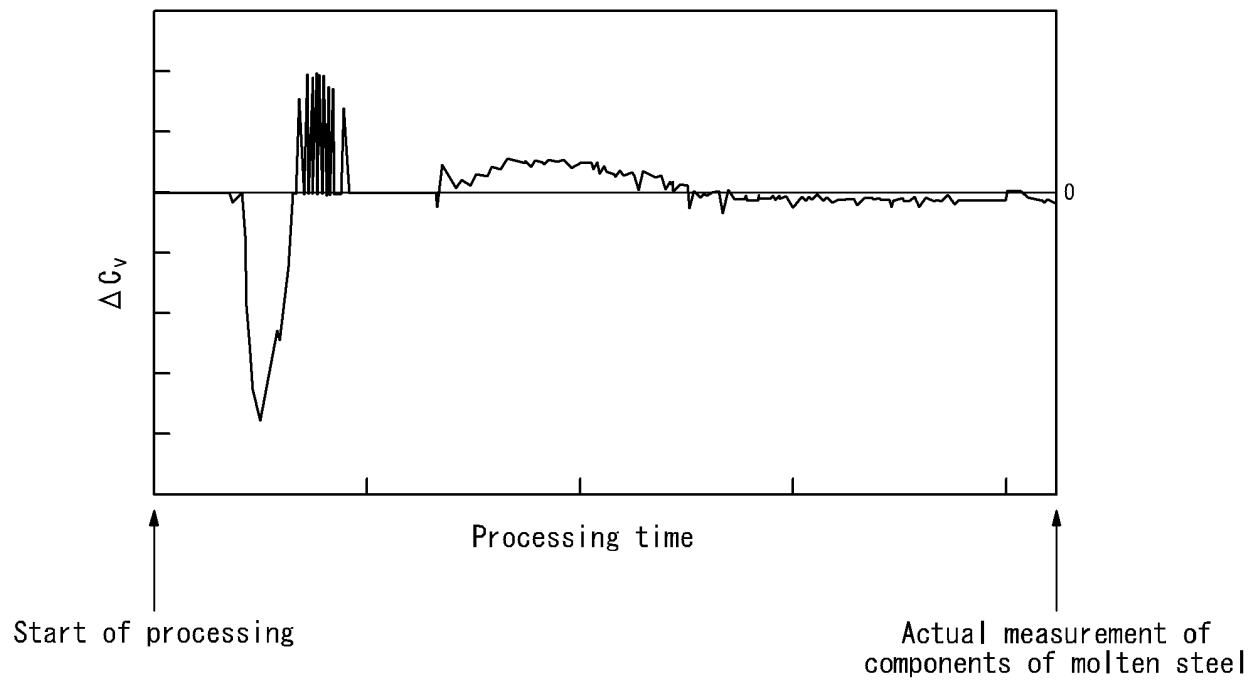


FIG. 4



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2023/016017

A. CLASSIFICATION OF SUBJECT MATTER

C21C 7/10(2006.01)i; **C21C 7/00**(2006.01)i; **C21C 7/068**(2006.01)i

FI: C21C7/10 P; C21C7/00 R; C21C7/068; C21C7/10 A

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)

C21C7/10; C21C7/00; C21C7/068

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	JP 11-279625 A (NKK CORP.) 12 October 1999 (1999-10-12) paragraphs [0001]-[0030]	1-10
Y	JP 2017-115216 A (JFE STEEL CORP.) 29 June 2017 (2017-06-29) paragraphs [0001]-[0050]	1-10
Y	JP 09-272913 A (NIPPON STEEL CORP.) 21 October 1997 (1997-10-21) paragraphs [0001]-[0023]	1-10

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

* Special categories of cited documents:

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Date of the actual completion of the international search

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Name and mailing address of the ISA/JP

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2023/016017

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JP	2017-115216	A	29 June 2017	(Family: none)	
JP	09-272913	A	21 October 1997	(Family: none)	

REFERENCES CITED IN THE DESCRIPTION

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- **YOSHIHIKO HIGUCHI et al.** Effects of [C], [O] and Pressure on RH Vacuum Decarburization. *Iron and Steel*, 1998, vol. 84 (10), 709-714 [0007]