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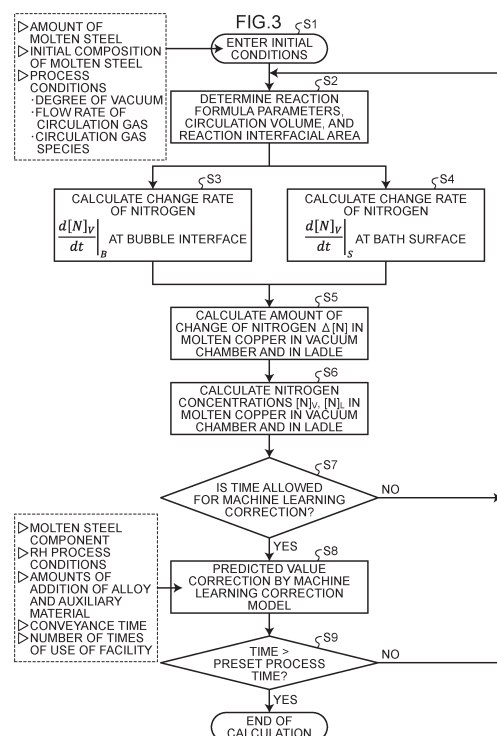
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(54) **NITROGEN CONCENTRATION PREDICTION METHOD, NITROGEN CONCENTRATION CONTROL METHOD, NITROGEN CONCENTRATION PREDICTION DEVICE, AND NITROGEN CONCENTRATION CONTROL DEVICE**

(57) A nitrogen concentration prediction method of the present invention includes a prediction step of calculating a predicted value of the nitrogen concentration in the molten steel under an operating condition to be predicted, by using a nitrogen concentration prediction model that is a physical model that uses, as an input variable, a condition of the vacuum degassing process, and uses, as an output variable, a predicted value of the nitrogen concentration in the molten steel under the condition; and a correction step of correcting the predicted value of the nitrogen concentration in the molten steel calculated in the prediction step, by using a machine learning correction model that is a machine learning model that uses, as an explanatory variable, the condition of the vacuum degassing process, and uses, as a target variable, a prediction error which is a difference value between the predicted value of the nitrogen concentration in the molten steel calculated under the condition with use of the nitrogen concentration prediction model, and an actual value.



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Description

Field

[0001] The present invention relates to a nitrogen concentration prediction method, a nitrogen concentration control method, a nitrogen concentration prediction apparatus, and a nitrogen concentration control apparatus. Background **[0002]** In general, molten steel processed in a converter or the like is conveyed to a secondary refining step, and the nitrogen concentration thereof is controlled by vacuum degassing process. Appropriate control of the nitrogen concentration in the molten steel contributes to enhance functionality of the steel product, so that the control needs to be as accurate as possible. Against the background, a lot of techniques for controlling the nitrogen concentration in the molten steel in the vacuum degassing process have been proposed. More specifically, Patent Literature 1 describes a method in which, in the first half of the vacuum degassing process, the process is conducted so as to control hydrogen concentration and oxygen concentration to predetermined levels or below, during which the nitrogen concentration in the molten steel is analyzed, then in the second half of the vacuum degassing process, process conditions are determined according to an analysis value of the nitrogen concentration. According to the method described in Patent Literature 1, the nitrogen concentration in the molten steel is predicted in consideration of nitriding and denitriding reactions at the surface of a molten steel bath in a vacuum chamber and at a bubble interface, nitriding reaction due to incoming atmospheric air through a dip tube, and mixing of the molten steel under circulation.

Citation List

Patent Literature

[0003] Patent Literature 1: JP 5836187 B2

Non Patent Literature

[0004]

Non Patent Literature 1: T. Kuwabara, K. Umezawa, K. Mori, and H. Watanabe: Trans. Iron Steel Inst. Jpn., 28(1988), 305

Non Patent Literature 2: Recommended Equilibrium Values for Steelmaking Reaction, edited by 19th Committee of Japan Society for the Promotion of Science, revised and enlarged: 1984

Non Patent Literature 3: T. Kitamura, K. Miyamoto, R. Tsujino, S. Mizoguchi, and K. Kato: ISIJ International, 36(1996), 395

Non Patent Literature 4: K. Harashima, S. Mizoguchi, H. Kajioka, and M. Sakakura: Tetsu-to-Hagane, 73(1987), 1559

Summary

Technical Problem

[0005] According to the method described in Patent Literature 1, the nitrogen concentration in the molten steel is predicted without considering influences of differences in the component and temperature for each molten steel to be processed, influences of auxiliary material to be added to the molten steel on the components of the molten steel or the vacuum degassing process, and influences of disturbance in process steps other than the vacuum degassing process, the conveyance step, and the like. Therefore, in the method described in Patent Literature 1, changes in the rate of change of nitrogen concentration due to the aforementioned influences will increase a prediction error of the nitrogen concentration, and this would make it difficult to accurately control the nitrogen concentration in the molten steel.

[0006] The present invention has been made in view of the above problem, and an object thereof is to provide a nitrogen concentration prediction method and a nitrogen concentration prediction apparatus, capable of accurately predicting the nitrogen concentration in the molten steel during the vacuum degassing process. Another object of the present invention is to provide a nitrogen concentration control method and a nitrogen concentration control apparatus, capable of accurately controlling the nitrogen concentration in the molten steel during the vacuum degassing process.

Solution to Problem

[0007] A nitrogen concentration prediction method for predicting a nitrogen concentration in molten steel in a vacuum degassing process, includes: a prediction step of calculating a predicted value of the nitrogen concentration in the molten steel under an operating condition to be predicted, by using a nitrogen concentration prediction model that is a physical model that uses, as an input variable, a condition of the vacuum degassing process, and uses, as an output variable, a predicted value of the nitrogen concentration in the molten steel under the condition; and a correction step of correcting the predicted value of the nitrogen concentration in the molten steel calculated in the prediction step, by using a machine learning correction model that is a machine learning model that uses, as an explanatory variable, the condition of the vacuum degassing process, and uses, as a target variable, a prediction error which is a difference value between the predicted value of the nitrogen concentration in the molten steel calculated under the condition with use of the nitrogen concentration prediction model, and an actual value.

[0008] The explanatory variable preferably includes a number of times of use of a facility of the vacuum degassing apparatus.

[0009] The correction step is preferably conducted, upon acquisition of the actual value of the nitrogen concentration in the molten steel.

[0010] A nitrogen concentration control method according to the present invention includes a step of controlling a condition of the vacuum degassing process according to the nitrogen concentration in the molten steel predicted by the nitrogen concentration prediction method according to the present invention.

[0011] The nitrogen concentration prediction method is preferably applied to a vacuum degassing process in which a flow rate of circulation gas per ton of the molten steel is in a range of 4 to 20 NL/min·ton, and a degree of vacuum in a vacuum chamber is 12/76 (atm) or less.

[0012] The nitrogen concentration prediction method is preferably applied to a vacuum degassing process in which a target value of the nitrogen concentration in the molten steel is in a range of 30 to 100 ppm.

[0013] A nitrogen concentration prediction apparatus for predicting a nitrogen concentration in molten steel in a vacuum degassing process, includes: a prediction means for calculating a predicted value of the nitrogen concentration in the molten steel under an operating condition to be predicted, by using a nitrogen concentration prediction model that is a physical model that uses, as an input variable, a condition of the vacuum degassing process, and uses, as an output variable, a predicted value of the nitrogen concentration in the molten steel under the condition; and a correction means for correcting the predicted value of the nitrogen concentration in the molten steel calculated by the prediction means, by using a machine learning correction model that is a machine learning model that uses, as an explanatory variable, the condition of the vacuum degassing process, and uses, as a target variable, a prediction error which is a difference value between the predicted value of the nitrogen concentration in the molten steel calculated under the condition with use of the nitrogen concentration prediction model, and an actual value.

[0014] A nitrogen concentration control apparatus includes a control means for controlling a condition of a vacuum degassing process, according to the nitrogen concentration in the molten steel predicted by the nitrogen concentration prediction apparatus according to the present invention.

Advantageous Effects of Invention

[0015] According to the nitrogen concentration prediction method and the nitrogen concentration prediction apparatus of the present invention, the nitrogen concentration in the molten steel during the vacuum degassing process can be accurately predicted. According to the nitrogen concentration control method and the nitrogen concentration control apparatus of the present invention, the nitrogen concentration in the molten steel during the vacuum degassing process can be accurately controlled.

Brief Description of Drawings

[0016]

[FIG. 1] FIG. 1 is a schematic diagram illustrating a structure of a vacuum degassing apparatus according to an embodiment of the present invention.

[FIG. 2] FIG. 2 is a diagram illustrating a prediction image of a nitrogen concentration, based on combination of a nitrogen concentration prediction model and a machine learning correction model.

[FIG. 3] FIG. 3 is a flowchart illustrating a flow of a nitrogen concentration prediction process according to an embodiment of the present invention.

Description of Embodiments

[0017] Hereinafter, a nitrogen concentration prediction method, a nitrogen concentration control method, a nitrogen concentration prediction apparatus, and a nitrogen concentration control apparatus according to an embodiment of the present invention will be described in detail with reference to the drawings.

[Vacuum Degassing Apparatus]

[0018] First, a structure of a vacuum degassing apparatus according to an embodiment of the present invention will be described with reference to FIG. 1.

[0019] FIG. 1 is a schematic diagram illustrating a structure of a vacuum degassing apparatus according to an embodiment of the present invention. As illustrated in FIG. 1, a vacuum degassing apparatus 1 according to an embodiment of the present invention has a ladle 2 in which molten steel S is accommodated, and a vacuum chamber 3 capable of controlling the inside to a vacuum state. To a lower portion of the vacuum chamber 3, two dip tubes 4 that communicate with the inside of the vacuum chamber 3 are provided, and in one of the dip tubes 4, a blow-in port 5 through which a circulation gas G is blown into the vacuum chamber 3 is formed. In the upper portion of the vacuum chamber 3, there is formed an exhaust port 6 through which a gas generated by the vacuum degassing process is discharged to the outside.

[0020] When conducting the vacuum degassing process with use of such a vacuum degassing apparatus, first, the lower ends of the two dip tubes 4 are immersed in the molten steel S accommodated in the ladle 2. Next, the inside of the vacuum chamber 3 is evacuated while blowing therein the circulation gas G such as argon gas or nitrogen gas through the blow-in port 5, thereby circulating the molten steel S between the ladle 2 and the vacuum chamber 3 for degassing process. Since the molten steel S herein in the vacuum chamber 3 is exposed to a reduced pressure atmosphere, a degassing reaction vigorously proceeds, whereby mainly decarburization process, denitrifying process, dehydrogenation process, and the like are allowed to proceed. The gas generated by the degassing reaction is discharged through the exhaust port 6 to the outside. Also the components of the molten steel S are adjusted, by concurrently charging alloy, auxiliary material, and the like into the molten steel S.

[0021] When the nitrogen concentration in the molten steel S needs to be controlled, the nitrogen concentration in the molten steel S is controlled by changing operating conditions such as switching of species of the circulation gas G, adjustment of flow rate of circulation gas G, and adjustment of the degree of vacuum in the vacuum chamber 3. For example, use of nitrogen gas as the circulation gas G will increase the rate of nitriding. Meanwhile, by increasing the degree of vacuum in the vacuum chamber 3 to further lower the pressure in the vacuum chamber 3, the rate of denitrifying in the vacuum chamber 3 will be increased. The nitrogen concentration in the molten steel S is controllable by such operations.

[0022] This sort of control of the operating conditions of the vacuum degassing apparatus 1 is implemented by a control apparatus 10 constituted by an information processor such as a computer. The control apparatus 10 controls the operating conditions of the vacuum degassing apparatus 1, according to information that indicates an operating state of the vacuum degassing apparatus 1 acquired from a sensor or the like attached to the vacuum degassing apparatus 1. In addition in the present embodiment, the control apparatus 10 functions as a nitrogen concentration prediction unit 11 and a correction unit 12, as a result of execution of a computer program by an arithmetic processing unit in the information processor. The nitrogen concentration prediction unit 11 uses the nitrogen concentration prediction model to predict the nitrogen concentration in the molten steel S, and controls the operating conditions of the vacuum degassing apparatus 1 according to the thus predicted nitrogen concentration, thereby controlling the nitrogen concentration in the molten steel S. The nitrogen concentration prediction model herein is a physical model that uses the operating condition of the vacuum degassing apparatus 1 as an input variable, and uses the predicted value of the nitrogen concentration in the molten steel S as an output variable. The correction unit 12 is structured to correct, with use of the machine learning correction model, the predicted value of the nitrogen concentration calculated by the nitrogen concentration prediction unit 11. The machine learning correction model herein is a machine learning model that uses, as an explanatory variable, the operating condition of the vacuum degassing apparatus 1, and uses, as a target variable, a prediction error which is a difference value between the predicted value of the nitrogen concentration calculated by the nitrogen concentration prediction unit 11 with use of the operating condition, and an actual value. The nitrogen concentration prediction model and the machine learning correction model will be detailed later.

[Nitrogen Concentration Prediction Model]

[0023] Next, the nitrogen concentration prediction model will be described.

[0024] Rates of change $d[N]_L/dt$ and $d[N]_V/dt$ of the nitrogen concentration in the molten steel S, in the ladle 2 and in the vacuum chamber 3, may be given by expressions (1) and (2) below, assuming complete mixing of the molten steel

S. In expressions (1) and (2), t represents time (sec), $[N]_V$ represents the nitrogen concentration (mass%) in the molten steel S in the vacuum chamber 3, V_V represents the volume (m^3) of the molten steel S in the vacuum chamber 3, Q represents the circulation volume (m^3/sec) of the molten steel S, $[N]_L$ represents the nitrogen concentration (mass%) in the molten steel S in the ladle 2, and V_L represents the volume (m^3) of the molten steel S in the ladle 2.

[Mathematical formula 1]

$$\frac{d[N]_V}{dt} = -\frac{Q}{V_V}([N]_V - [N]_L) + \left. \frac{d[N]_V}{dt} \right|_S + \left. \frac{d[N]_V}{dt} \right|_B \quad \dots (1)$$

[Mathematical formula 2]

$$\frac{d[N]_L}{dt} = -\frac{Q}{V_L}([N]_V - [N]_L) \quad \dots (2)$$

[0025] In expression (1), each term on the right side represents, in the order from the first term, mixing of the molten steel S between the vacuum chamber 3 and the ladle 2 under circulation, the rate of change of the nitrogen concentration on the surface of the molten steel bath in the vacuum chamber 3, and the rate of change of the nitrogen concentration in the circulation gas at the bubble interface. On the other hand, expression (2) considers mixing of the molten steel S between the vacuum chamber 3 and the ladle 2 under circulation.

[0026] Note that the circulation volume Q of the molten steel S in expressions (1) and (2) may be calculated, with use of expression (3) below, with reference to the description of Non Patent Literature 1. In expression (3), Q_g represents the flow rate of circulation gas (Nm^3/min), D represents the diameter of dip tube 4 (m), and P_V represents the pressure (atm) in the vacuum chamber 3.

[Mathematical formula 3]

$$Q = 11.4 Q_g^{1/3} D^{4/3} \left(\ln \frac{1}{P_V} \right)^{1/3} \quad \dots (3)$$

[0027] In the present embodiment, the rate of change in the nitrogen concentration at each of the reaction sites for the nitriding and denitriding reactions assumes mixed rate limiting by mass transfer on the molten steel side and the chemical reaction at the gas-liquid interface, as given by expression (4) below. With this, expression (4) is rearranged to give expression (5) below, as an expression that describes the reaction rate of nitrogen in the molten steel S in the vacuum chamber 3. The nitrogen concentration prediction model therefore calculates a predicted value of the nitrogen concentration in the molten steel S, upon entry of necessary numerical values into expression (5) below. In expressions (4) and (5), A represents a gas-liquid reaction interfacial area (m^2), k_m represents a mass transfer coefficient of nitrogen on the molten steel side (m/sec), k_r represents a rate constant of chemical reaction of nitrogen (m/sec-mass%), $[N]_i$ represents the nitrogen concentration on the molten steel side of the gas-liquid interface (mass%), and $[N]_{eq}$ represents the nitrogen concentration in the molten steel under equilibrium with nitrogen gas in the gas phase (equilibrium nitrogen concentration) (mass%).

[Mathematical formula 4]

$$\frac{d[N]_V}{dt} = -\frac{A}{V_V} k_m ([N]_V - [N]_i) = -\frac{A}{V_V} k_r ([N]_i^2 - [N]_{eq}^2) \quad \dots (4)$$

[Mathematical formula 5]

$$\frac{d[N]_V}{dt} = -\frac{A}{V_V} \left\{ k_m [N]_V - k_m \left(\frac{-k_m + \sqrt{k_m^2 + 4k_m k_r [N]_V + 4k_r^2 [N]_{eq}^2}}{2k_r} \right) \right\} \quad \dots (5)$$

[0028] The reaction sites where the rate of change of the nitrogen concentration is calculated with use of expression (5) include the surface of the molten steel bath in the vacuum chamber 3, and the bubble interface, wherein the difference lies in gas-liquid reaction interfacial area A and equilibrium nitrogen concentration $[N]_{eq}$. Among these, the equilibrium nitrogen concentration $[N]_{eq}$ may be calculated, with use of expression (6) below, with reference to the

description of Non Patent Literature 2. In expression (6), f_N represents an activity coefficient of nitrogen, P_{N_2} represents a partial pressure of nitrogen, R represents the gas constant (J/K·mol), and T represents a temperature (K) of the molten steel S.

[Mathematical formula 6]

$$[N]_{eq} = \frac{\sqrt{P_{N_2}}}{f_N} \exp\left(-\frac{9916 + 20.17 T}{RT}\right) \quad \dots (6)$$

[0029] The activity coefficient f_N of nitrogen in expression (6) is calculated, while considering influences of C, Si, Mn, and O as the main components. More specifically, the activity coefficient f_N of nitrogen is calculated by expression (7) below, with use of the values listed in Table 1 below, as the first-order interaction coefficients between each of these components and nitrogen described in Non Patent Literature 2. In expression (7), e_N^j represents the first-order interaction coefficient ($j = C, Si, Mn, O$) with nitrogen. Note that the components listed above are examples, and it is obvious that the components to be considered will actually increase or decrease depending on the component system of the steel species to be processed.

[Table 1]

[0030]

(Table 1)

	j			
	C	Si	Mn	O
N	0.13	0.048	-0.02	-0.02

[Mathematical formula 7]

$$\log f_N = e_N^C[\text{mass}\%C] + e_N^{Si}[\text{mass}\%Si] + e_N^{Mn}[\text{mass}\%Mn] + e_N^O[\text{mass}\%O] \quad \dots (7)$$

[0031] On the other hand, the mass transfer coefficient k_m of nitrogen on the molten steel side in expression (5) may be calculated, with use of expressions (8) to (12) below, with reference to the description of Non Patent Literature 3. In expressions (8) to (12), the mass transfer coefficient k_m of nitrogen on the molten steel side is determined, in consideration of the time for replacement of the molten steel S around the bubble. In expressions (8) to (12), θ represents a contact time (min) of the molten steel S with the bubble, D_N represents a diffusion coefficient (m²/min) of nitrogen, d_B represents the diameter of blown bubble (m), U_B represents a rising speed of bubble (m/min), U_L represents a rising speed of molten steel (m/min), g represents the gravitational acceleration (m/s²), and L represents a height of the bath surface (m) in the vacuum chamber 3 above a position where the circulation gas is blown.

[Mathematical formula 8]

$$k_m = 2\sqrt{D_N/(\pi \cdot \theta)} \quad \dots (8)$$

[Mathematical formula 9]

$$\theta = d_B/U \quad \dots (9)$$

[Mathematical formula 10]

$$U = U_B + U_L \quad \dots (10)$$

[Mathematical formula 11]

$$U_B = \sqrt{0.5 \cdot g \cdot d_B} \quad \dots (11)$$

[Mathematical formula 12]

$$U_L = 19.9 \cdot \frac{Q}{D^2} \cdot (g \cdot D^5)^{0.24} \cdot \left(\frac{L}{D}\right)^{0.2} \quad \dots (12)$$

[0032] Meanwhile, the rate constant k_r of chemical reaction of nitrogen in expression (5) may be calculated, with use of expression (13) below, with reference to the description of Non Patent Literature 4. In expression (13), [O] represents oxygen concentration (mass%) in the molten steel S, and [S] represents sulfur concentration (mass%) in the molten steel S.

[Mathematical formula 13]

$$k_r = \frac{15.0 f_N^2}{(1 + 28.4[O] + 63.4[S])^2} \quad \dots (13)$$

[0033] When considering the reaction rate on the surface of the molten steel bath and the reaction rate at the bubble interface, with respect to the gas-liquid reaction interfacial area A in expression (5), the molten steel bath surface area, and the bubble interfacial area respectively serve as such gas-liquid reaction interfacial area. Assuming now that the molten steel bath surface area is proportional to 2/3 of the circulation volume Q , and that the bubble interfacial area is proportional to the 2/3 power of the flow rate of circulation gas Q_g , these areas may be estimated by expressions (14) and (15) below. In expressions (14) and (15), α_S and α_B represent respective proportional constants. Another conceivable method for estimating the gas-liquid reaction interfacial area may be a calculation method in consideration of physical behaviors of the bubble or the surface area of the molten steel bath, with use of the flow rate of circulation gas, the circulation gas species, the degree of vacuum, and the like.

[Mathematical formula 14]

$$A_S = \alpha_S \cdot Q^{2/3} \quad \dots (14)$$

[Mathematical formula 15]

$$A_B = \alpha_B \cdot Q_g^{2/3} \quad \dots (15)$$

[0034] On the other hand, the reaction that occurs at the nitrogen bubble interface upon blowing of nitrogen gas will be either a nitriding reaction or a denitriding reaction, depending on magnitude relation between the nitrogen concentration in the molten steel S, and the nitrogen concentration under equilibrium with the nitrogen partial pressure in the nitrogen bubble. In addition, the blown nitrogen bubble will rise up in the molten steel, so that the nitrogen partial pressure in the nitrogen bubble will decrease due to change in the static pressure exerted from the molten steel. Accordingly, the rate of reaction and the direction of reaction of the rising nitrogen bubble will not be constant. The nitrogen concentration prediction model therefore employs expression (16) below, in which these matters are taken into consideration, to calculate the rate of change of the nitrogen concentration at the nitrogen bubble interface. $[N]_{eq}(x)$ in expression (16) represents an equilibrium nitrogen concentration (mass%) in the nitrogen bubble at a rising distance x from the blowing position of the circulation gas, and may be calculated with use of expression (6) described previously.

[Mathematical formula 16]

$$\begin{aligned} \frac{d[N]_v}{dt} &= \int_0^h \frac{d[N]_v}{dt} \Big|_x dx \quad \dots (16) \\ &= \int_0^h -\frac{A}{V_v} \left\{ k_m [N]_v - k_m \left(\frac{-k_m + \sqrt{k_m^2 + 4k_m k_r [N]_v + 4k_r^2 [N]_{eq}^2(x)}}{2k_r} \right) \right\} dx \end{aligned}$$

[Machine Learning Correction Model]

[0035] Next, the machine learning correction model will be described.

[0036] The reason why the machine learning model is used to correct the predicted value of the nitrogen concentration is to consider a difference in operating conditions and influence of disturbance, which are difficult to consider only by prediction with a physical model which can degrade the prediction accuracy of the nitrogen concentration. Review of the process results of the vacuum degassing process revealed that some of the results gave different rates of change in the nitrogen concentration, even under almost the same circulation gas pattern, the degree of vacuum, and nitrogen concentration. That is, there is a case where the variation in the change rate of the nitrogen concentration cannot be explained only by simple vacuum degassing process conditions. In such a case, prediction calculation of the nitrogen concentration with use of the physical model will degrade the prediction accuracy of the nitrogen concentration. A plurality of causes of different denitrifying behaviors under substantially the same process conditions are conceivable. Several causes will be exemplified below.

[0037] The first cause relates to influence of the molten steel components. Although influences of C, Si, P, Mn, O, and S are considered also in the aforementioned nitrogen concentration prediction model, the model takes only direct influences on changes in the nitrogen concentration into account, while leaving the changes in the temperature and the change in the slag composition, due to difference in these components or the component change during the vacuum degassing process unconsidered.

[0038] The second cause relates to influences of alloy or auxiliary material to be added. Besides the change in the components of the molten steel due to the addition of the alloy or the auxiliary material, expected occurrence includes entry of impurity component, change in the molten steel temperature, influence on molten steel flow, and changes in the degree of vacuum and the atmosphere during the addition, which would affect the change rate of the nitrogen concentration on occasion.

[0039] The third cause relates to influences outside the vacuum degassing process. Process state in a converter, which is a process that precedes the vacuum degassing process, or the time or environment before the molten steel is conveyed to the vacuum degassing apparatus would change the state of the molten steel at the start of the process. There may be a case where the molten steel is not analyzed at the start of the vacuum degassing process, and instead, analysis values of the molten steel immediately after the output from the converter are used as initial conditions of the molten steel including the nitrogen concentration, due to constraints of process time and steps. The case is, however, susceptible to influences outside the vacuum degassing process.

[0040] The denitrifying behavior seems to change due to such causes. It is, however, difficult to evaluate how these causes affect the rate of denitrifying, and it is also very difficult to separate the influences of the plurality of causes. Moreover, besides the aforementioned causes, there may even be any influence that is not easily conceived. As a matter of course, it is not easy to formulate these influences and reflect them in the physical model, to improve the prediction accuracy.

[0041] From intensive studies on measures against such problems, it was found effective to use machine learning with operating conditions as the feature. The machine learning can evaluate complicated influences ascribed to an entered feature at a time, without needing a logic describing how they affect, and is therefore useful as a solution to the aforementioned problem.

[0042] The machine learning model created in the present invention is a regression prediction model, structured to predict a target variable from an explanatory variable called feature. Creation of the machine learning model therefore needs to set the target variable, and to select an appropriate feature. From examination, deviation of the predicted value of the nitrogen concentration based on the physical model was considered to be an effective target variable. For a prediction model of a physical quantity with use of the machine learning, a fitting parameter in reaction formula is often used as the target variable. This is applicable when it is found, from the result of examination of the reaction, that any unknown parameter which cannot be derived from existing numerical values is obviously present. In other words, this is applicable in a case where how the feature used in the machine learning contributes to a physical reaction has been understood to some extent. For the aforementioned problem, it is, however, difficult to understand just how the influences are exerted, and also a number of influential factors present there would mutually interfere. Such technique is therefore not applicable.

[0043] Therefore for the present embodiment, an error between the prediction result by the physical model and the actual value was used as the target variable, rather than using the parameters in the physical model as the target variable. This makes it possible to separate the target variable from the calculation of the physical model, and to isolate the machine learning model from the prediction in consideration of the reaction theory by the physical model, whereby the machine learning is also applicable to the aforementioned problem. Also the method is widely applicable regardless of calculation technique by the physical model, which is a secondary benefit of this method. What is required as learning data for the machine learning is a calculation result of the physical model, so that accuracy improvement by the machine learning is expectable regardless of accuracy or theory of the physical model itself. This

means that the machine learning is easily introduced, and is applicable not only to the vacuum degassing process but also to many processes.

[0044] Other advantages are exemplified by simplicity of accuracy verification, remodeling, and the like, since the physical model and the machine learning model are almost independent. In the method of determining the parameters in the physical model by the machine learning model, one prediction result is output. If the accuracy is poor, it is however not always easy to determine which of the physical model or the machine learning model has the accuracy problem. According to the present method, the prediction result by the physical model, and the correction result by the machine learning model that corrects the predicted result are separately obtainable, making it easy to separately evaluate the accuracy of the individual models. Also verification and remodeling for improving the prediction accuracy of the individual models are easy.

[0045] For selection of the feature, variables that can affect the denitrifying behavior, from among the operating conditions, were examined, and a machine learning model was actually created to evaluate contribution of each feature to the accuracy. Therefore, molten steel component, circulation gas pattern, the degree of vacuum, amounts of addition of alloy and auxiliary material, conveyance time from a previous process, and the like, which are generally considered to be influential, were selected as the feature. Other than these, the number of times of use of the facility, such as the number of times of use of the ladle, the number of times of use of the dip tube, and the number of times of use of the vacuum chamber, were found to be largely influential to the accuracy. In the steel refining process, a thermodynamic examination into the reaction is a main issue. On the other hand in the vacuum degassing process, physical behavior of the molten steel, centered round the gas-liquid reaction interfacial area, is important. Accordingly, the refractory would change the shape depending on the number of times of use of the facility, whereby the flow of molten steel during the vacuum degassing process would change, and this presumably affects the denitrifying behavior. For this reason, largeness of the influence of the number of times of use of the facility is considered to be a unique point in the vacuum degassing processing, and to be important information that greatly affects the prediction accuracy.

[0046] The importance of the aforementioned number of times of use of the facility, as the feature, does not depend on the type of the target variable. That is, in most cases where the machine learning is used for implementing the prediction and control related to the denitrifying reaction of the vacuum degassing process, selection of the number of times of use of the facility as the feature is understood to be highly effective. Note, however, that this examination is considered to be well applicable to a process conducted with a flow rate of circulation gas per ton of the molten steel of 4 to 20 (NL/min·ton), in the range of degree of vacuum in the vacuum chamber <12/76 (atm). From a simulation of the molten steel flow by numerical analysis, it was found that the flow of the molten steel becomes anomalous outside the aforementioned ranges, so that the influence of the difference in the shape of the refractory, depending on the number of times of use of the facility, will not be effectively considered. More specifically, if the flow rate of circulation gas is extremely small, or if the degree of vacuum in the vacuum chamber is small, the amount of circulation molten steel will be very small. If the flow rate of circulation gas is extremely large, agitation by the bubble will be large, and also the disturbance of the surface of the molten steel bath will become large. In these cases, the influence of the refractory at a location different from the refractory portion that affects the molten steel in the normal process would become large, and this would make it unable to understand the influence simply by the number of times of use of the facility. Therefore, the accuracy of machine learning will degrade outside the aforementioned ranges. It is, however, considered highly probable that the method of the present invention is effective to improve the control accuracy even outside the aforementioned ranges of numerical conditions, by modifying the physical model or optimizing the machine learning model, assuming such ranges of process conditions.

[0047] An algorithm used for the machine learning is not particularly limited, for which an appropriate algorithm is selected according to the situation of facility that differs for each facility, and characteristics of the number of pieces of learning data. In the embodiment of the present invention, a model was created with use of gradient boosting based on a decision tree algorithm. It has, however, been confirmed that comparable accuracy is also obtainable by many algorithms such as random forest and neural network.

[0048] Next, a method of correcting the nitrogen concentration by the machine learning correction model will be described. In the present embodiment, what is used as the target variable by the machine learning correction model is an error $[N]_{\text{Error}}$ (mass%) between the predicted value by the nitrogen concentration prediction model, and an actual value, given by expression (17) below. In expression (17), $[N]_{\text{Result}}$ represents the actual value (mass%) of the nitrogen concentration, and $[N]_{\text{Phys-Calc}}$ represents a predicted value (mass%) of the nitrogen concentration with use of the nitrogen concentration prediction model.

[Mathematical formula 17]

$$[N]_{\text{Error}} = [N]_{\text{Result}} - [N]_{\text{Phys-Calc}} \quad \dots (17)$$

[0049] The machine learning correction model that uses the error $[N]_{\text{Error}}$ as the target variable may be interpreted

as being able to predict how the predicted value by the nitrogen concentration prediction model deviates under a given operating condition. Therefore as given by expression (18) below, the predicted value by the nitrogen concentration prediction model may be corrected to a value closer to the actual value, by using this predicted error. In expression (18), $[N]_{\text{Prediction}}$ represents a final predicted value (mass%) of the nitrogen concentration, and $[N]_{\text{prediction Error}}$ represents a prediction error (mass%) obtained from the machine learning correction model.

$$[N]_{\text{Prediction}} = [N]_{\text{Phys-Calc}} - [N]_{\text{Error}}^{\text{Prediction}} \quad \dots (18)$$

[0050] A prediction image of the nitrogen concentration, based on combination of the nitrogen concentration prediction model and the machine learning correction model, is illustrated in FIG. 2. As illustrated in FIG. 2, the prediction by the nitrogen concentration prediction model progresses from a process start point, during which the correction takes place at process times (10 minutes, 20 minutes, and 30 minutes, in this example) where the correction by the machine learning correction model is applicable. The prediction by the nitrogen concentration prediction model proceeds again from the predicted value of the nitrogen concentration thus corrected. Such flow is repeated also thereafter, to predict the nitrogen concentration at the end of process. A necessary condition, under which the machine learning correction model is applicable, is that past actual values capable of serving as the learning data are available at a certain process time. The correction in this case can take place only at the process time when the analysis has taken place and the actual values of the nitrogen concentration have been accumulated. For example in a process case where the actual value data has been acquired by sampling at the process times of 10 minutes and 20 minutes, and at the end of process, the predicted values by the nitrogen concentration prediction model at these process times are correctable.

[0051] The higher the frequency of the correction by machine learning, the more the prediction accuracy tends to improve. The machine learning correction is substantially enabled at the time of intermediate analysis, so that a process pattern having a higher frequency of intermediate analysis will be more expectable for improvement in the control accuracy by the present invention. More specifically, higher control accuracy is expectable for a process in which the machine learning correction takes place once or more times per the process time of 15 minutes, or in which the machine learning takes place at least once or more, within a period between the scheduled process end time and a point in time 15 minutes before it. The value of 15 minutes was found out, while balancing the accuracy of the nitrogen concentration prediction model, the charge frequency of alloy and auxiliary material, the time required for melting and homogenization of alloy and auxiliary material, the frequency of sample collection, the time required for analysis, and the like.

[0052] When creating the machine learning correction model, the learning data volume is preferably as large as possible. Therefore, for a case where a large volume of past records of the nitrogen concentration control directed to similar steel species are available, application of the present invention will give a distinct improvement in the prediction accuracy. In many of the steel species in need of the nitrogen concentration control to which the present invention is applied, the target nitrogen concentration falls in the range of 30 to 100 ppm. Improvement in the prediction accuracy was confirmed particularly in this range. In a case where a target nitrogen concentration of less than 30 ppm is aimed at, the denitrifying process will take place over a long duration of time, although it depends on the nitrogen concentration value before the process. Conversely, in a case where the target nitrogen concentration is larger than 100 ppm, the nitriding process often takes place over a long duration of time.

[0053] In such a case, the nitrogen concentration control is different in nature from nitrogen concentration control in which the nitriding process and the denitrifying process are switched, aiming at the control within a range between the upper and lower limits on both sides of the target nitrogen concentration value, which is the main object of the present invention. In addition, the obtainable actual data will lack diversity of data, while being biased either towards the nitriding or denitrifying process. Incorporation of such extreme data into the learning data group would degrade the prediction accuracy. Therefore, application to the steel species having the target nitrogen concentration in the range from 30 to 100 ppm is preferred, in order to keep the prediction accuracy at a high level. Note, the prediction per se is possible at higher accuracy than in the prior art, even for the steel species out of the aforementioned range. In addition, it is probable enough that a method, based on switching of the nitrogen concentration prediction model and the machine learning correction model for each target nitrogen concentration, is used to improve the prediction accuracy in different target nitrogen concentration ranges.

[Nitrogen Concentration Prediction Process]

[0054] Lastly, a flow of the nitrogen concentration prediction process according to one embodiment of the present invention will be described, with reference to FIG. 3.

[0055] FIG. 3 is a flowchart illustrating a flow of a nitrogen concentration prediction process according to an embodi-

ment of the present invention. The flowchart illustrated in FIG. 3 starts at the time (step S1) the initial conditions are entered to the control apparatus 10, and an execution command of the nitrogen concentration prediction process is entered to the control apparatus 10. The nitrogen concentration prediction process then advances to a process of step S2. Examples of the initial conditions entered to the control apparatus 10 include the amount of molten steel, initial composition of the molten steel, and conditions of the vacuum degassing process (degree of vacuum, flow rate of circulation gas, circulation gas species, etc.).

[0056] In the process of step S2, the control apparatus 10 determines parameters used for calculating the molten steel-side mass transfer coefficient of nitrogen, the chemical reaction rate constant, the activity coefficient, and the like in the reaction formula contained in the nitrogen concentration prediction model, the circulation volume, and the reaction interfacial area. Upon this, the process of step S2 is completed, and the nitrogen concentration prediction process then advances to processes of steps S3 and S4.

[0057] In the process of step S3, the control apparatus 10 calculates the rate of change of the nitrogen concentration at the bubble interface, with use of the nitrogen concentration prediction model. Upon this, the process of step S3 is completed, and the nitrogen concentration prediction process then advances to a process of step S5.

[0058] In the process of step S4, the control apparatus 10 calculates the rate of change of the nitrogen concentration at the surface of the molten steel bath in the vacuum chamber, with use of the nitrogen concentration prediction model. Upon this, the process of step S4 is completed, and the nitrogen concentration prediction process then advances to a process of step S5.

[0059] In the process of step S5, the control apparatus 10 calculates the amounts of change $\Delta[N]$ of the nitrogen concentrations in the vacuum chamber and in the molten steel in the ladle, with use of the rate of change of the nitrogen concentration at the bubble interface calculated by the process of step S3, and the rate of change of the nitrogen concentration on the surface of the molten steel bath in the vacuum chamber calculated by the process of step S4. Upon this, the process of step S5 is completed, and the nitrogen concentration prediction process then advances to a process of step S6.

[0060] In the process of step S6, the control apparatus 10 calculates the nitrogen concentrations $[N]_V$, $[N]_L$ of the molten steel in the vacuum chamber and in the ladle, with use of the amounts of change $\Delta[N]$ of the nitrogen concentrations in the molten steel in the vacuum chamber and in the ladle calculated by the process of step S5. Upon this, the process of step S6 is completed, and the nitrogen concentration prediction process then advances to a process of step S7.

[0061] In the process of step S7, the control apparatus 10 determines whether or not the current time is a time allowed for the machine learning correction. If the determination teaches that the current time is not the time allowed for the machine learning correction (step S7: No), the control apparatus 10 returns the nitrogen concentration prediction process to the process of step S2. On the other hand, if the current time is the time allowed for the machine learning correction (step S7: Yes), the control apparatus 10 advances the nitrogen concentration prediction process to the process of step S8.

[0062] In the process of step S8, the control apparatus 10 calculates the prediction error of the nitrogen concentration prediction model, by entering the operating condition of the vacuum degassing process to the machine learning correction model. The control apparatus 10 then uses the thus calculated prediction error to correct the nitrogen concentrations $[N]_V$ and $[N]_L$ of the molten steel in the vacuum chamber and in the ladle, calculated in the process of step S6. Upon this, the process of step S8 is completed, and the nitrogen concentration prediction process then advances to a process of step S9.

[0063] In the process of step S9, the control apparatus 10 determines whether or not the calculated time for the vacuum degassing process exceeds a preset process time. If the determination teaches that the calculated time for the vacuum degassing process does not exceed the preset process time (step S9: No), the control apparatus 10 increases the time for the vacuum degassing process by a predetermined duration, and then returns the nitrogen concentration prediction process back to the process of step S2. On the other hand, in a case where the calculated time for the vacuum degassing process exceeds the preset process time (step S9: Yes), the control apparatus 10 ends a series of nitrogen concentration prediction processes. Thereafter, the operator compares the predicted value and the target value of the nitrogen concentration, and corrects the process condition for adjusting the nitrogen concentration, according to the result of comparison. Examples of the process conditions include circulation gas species, flow rate of circulation gas, process time for vacuum degassing, and the degree of vacuum.

[Examples]

[0064] In this Example, a plurality of steel types was subjected to the nitrogen concentration control. The molten steel before the vacuum degassing process contains components in the ranges of $[C] < 0.1\%$, $[P] < 0.01\%$, $[S] < 0.01\%$, $[Mn] = 0.02$ to 1.2% , $[Si] = 0.1$ to 4.0% , and $[Al] < 0.1\%$. The target nitrogen concentration was 20 to 120 ppm, the molten steel temperature was 1480 to 1630°C, and the process amount of molten steel was 180 to 240 ton.

Nitrogen gas or argon gas was used as the circulation gas, wherein the flow rate of circulation gas was 1000 to 3000 (NL/min), the degree of vacuum during stabilized process was 12/76 (atm) or below, and the circulation process time was 30 minutes. During the process, the nitrogen concentration was analyzed at a plurality of times of sampling, and recorded as actual values.

[0065] The control method was conducted by entering initial conditions at the start of process, to determine the process conditions. The nitrogen concentration was predicted according to the process conditions, wherein if the predicted nitrogen concentration at the end of process and the target value differ by a certain value or more, the nitrogen concentration was controlled by correcting the process conditions. Upon acquisition of each actual value by the nitrogen concentration analysis during the process, the nitrogen concentration was predicted again from the actual value, and the process conditions were similarly corrected if necessary. A difference value between the predicted value and the target value, which gives a criterion for the correction of process conditions, needs to be appropriately determined according to change behavior of the nitrogen concentration which will differ depending on the facility, the molten steel components, and the molten steel conditions, and accuracy of the nitrogen concentration prediction model, and was set to 2 ppm in Example. The control was conducted as described above, and the control accuracy was evaluated from the result. Results of the evaluation of control accuracy are summarized in Table 2. The evaluation was made for about hundred charges per example, wherein the evaluation method employed standard deviation σ of difference between the target value and the actual value at the end of process, and percentage of deviation from target nitrogen concentration range ± 5 ppm.

[Table 2]

[0066]

(Table 2)

	Machine learning correction	Feature regarding number of times of use of facility	Characteristic of process condition	Process completion time	Process time allowed for analysis and machine learning correction	σ of target value - actual value (ppm)	Percentage of deviation from ± 5 ppm	Model evaluation
Example 1	Applied	Applied	-	30 min	12 min, 22 min, end of process	1.82	0.9	○
Example 2	Applied	Not applied	-		12 min, 22 min, end of process	2.02	1.4	○
Example 3	Applied	Applied	-		14 min, end of process	2.26	2.8	○
Example 4	Applied	Applied	-		7 min, 14 min, end of process	2.17	2.3	○
Example 5	Applied	Applied	Target[N] < 30ppm		12 min, 22 min, end of process	2.47	4.2	○
Example 6	Applied	Applied	Target[N] > 100ppm		7 min, 19 min, end of process	2.56	4.9	○
Example 7	Applied	Applied	Flow rate of circulation gas > 20NL/min·ton		10 min, 25 min, end of process	2.69	6.1	○
Comparative Example 1	Not applied	-	-		-	3.51	15.8	×

[0067] As summarized in Table 2, great improvement in the control accuracy was found in Examples 1 to 4, as compared with Comparative Example that employed a prior technique. From comparison between Example 1 and Example 2, even Example 2 was found to demonstrate higher accuracy as compared with Comparative Example. Usage of the number of times of use of the facility as the feature was, however, found to more distinctively improve the control accuracy. Examples 1, 3, and 4 employed different process timings for the analysis and the machine learning correction, wherein low frequency of correction, such as in Example 3, was found to degrade the accuracy. Example 4, whose number of times of correction was the same as that in Example 1, was found to degrade the control accuracy, since the correction is concentrated in the first half of the process, but is absent in a duration close to the end of process. From the results, it was confirmed that high control accuracy was obtainable by keeping a sufficient number of times of correction as in Example 1, and by conducting the correction in a duration close to the end of process.

[0068] Having described the embodiments to which the invention made by the present inventors was applied, the present invention is, however, not limited by the description and drawings that constitute a part of the disclosure of the present invention according to the present embodiments. That is, all the other embodiments, Examples, operation techniques, and the like, made by those skilled in the art while referring to the present embodiment, are included in the scope of the present invention.

Industrial Applicability

[0069] According to the present invention, the nitrogen concentration prediction method and the nitrogen concentration prediction apparatus, capable of accurately predicting the nitrogen concentration in the molten steel during the

vacuum degassing process, may be provided. According to the present invention, also the nitrogen concentration control method and the nitrogen concentration control apparatus, capable of accurately controlling the nitrogen concentration in the molten steel during the vacuum degassing process, may be provided.

Reference Signs List

[0070]

- 1 VACUUM DEGASSING APPARATUS
- 2 LADLE
- 3 VACUUM CHAMBER
- 4 DIP TUBE
- 5 BLOW-IN PORT
- 6 EXHAUST PORT
- 10 CONTROL APPARATUS
- 11 NITROGEN CONCENTRATION PREDICTION UNIT
- 12 CORRECTION UNIT
- G CIRCULATION GAS
- S MOLTEN STEEL

Claims

1. A nitrogen concentration prediction method for predicting a nitrogen concentration in molten steel in a vacuum degassing process,
the nitrogen concentration prediction method comprising:

a prediction step of calculating a predicted value of the nitrogen concentration in the molten steel under an operating condition to be predicted, by using a nitrogen concentration prediction model that is a physical model that uses, as an input variable, a condition of the vacuum degassing process, and uses, as an output variable, a predicted value of the nitrogen concentration in the molten steel under the condition; and
a correction step of correcting the predicted value of the nitrogen concentration in the molten steel calculated in the prediction step, by using a machine learning correction model that is a machine learning model that uses, as an explanatory variable, the condition of the vacuum degassing process, and uses, as a target variable, a prediction error which is a difference value between the predicted value of the nitrogen concentration in the molten steel calculated under the condition with use of the nitrogen concentration prediction model, and an actual value.

2. The nitrogen concentration prediction method according to claim 1, wherein the explanatory variable includes a number of times of use of a facility of the vacuum degassing apparatus.

3. The nitrogen concentration prediction method according to claim 1 or 2, wherein the correction step is conducted, upon acquisition of the actual value of the nitrogen concentration in the molten steel.

4. A nitrogen concentration control method comprising a step of controlling the condition of the vacuum degassing process, according to the nitrogen concentration in the molten steel predicted by the nitrogen concentration prediction method according to any one of claims 1 to 3.

5. A nitrogen concentration prediction apparatus for predicting a nitrogen concentration in molten steel in a vacuum degassing process,
the nitrogen concentration prediction apparatus comprising:

a prediction means for calculating a predicted value of the nitrogen concentration in the molten steel under an operating condition to be predicted, by using a nitrogen concentration prediction model that is a physical model that uses, as an input variable, a condition of the vacuum degassing process, and uses, as an output variable, a predicted value of the nitrogen concentration in the molten steel under the condition; and
a correction means for correcting the predicted value of the nitrogen concentration in the molten steel calculated by the prediction means, by using a machine learning correction model that is a machine learning model that uses, as an explanatory variable, the condition of the vacuum degassing process, and uses, as a target

variable, a prediction error which is a difference value between the predicted value of the nitrogen concentration in the molten steel calculated under the condition with use of the nitrogen concentration prediction model, and an actual value.

- 5 **6.** A nitrogen concentration control apparatus comprising a control means for controlling a condition of a vacuum degassing process, according to the nitrogen concentration in the molten steel predicted by the nitrogen concentration prediction apparatus according to claim 5.

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FIG.1

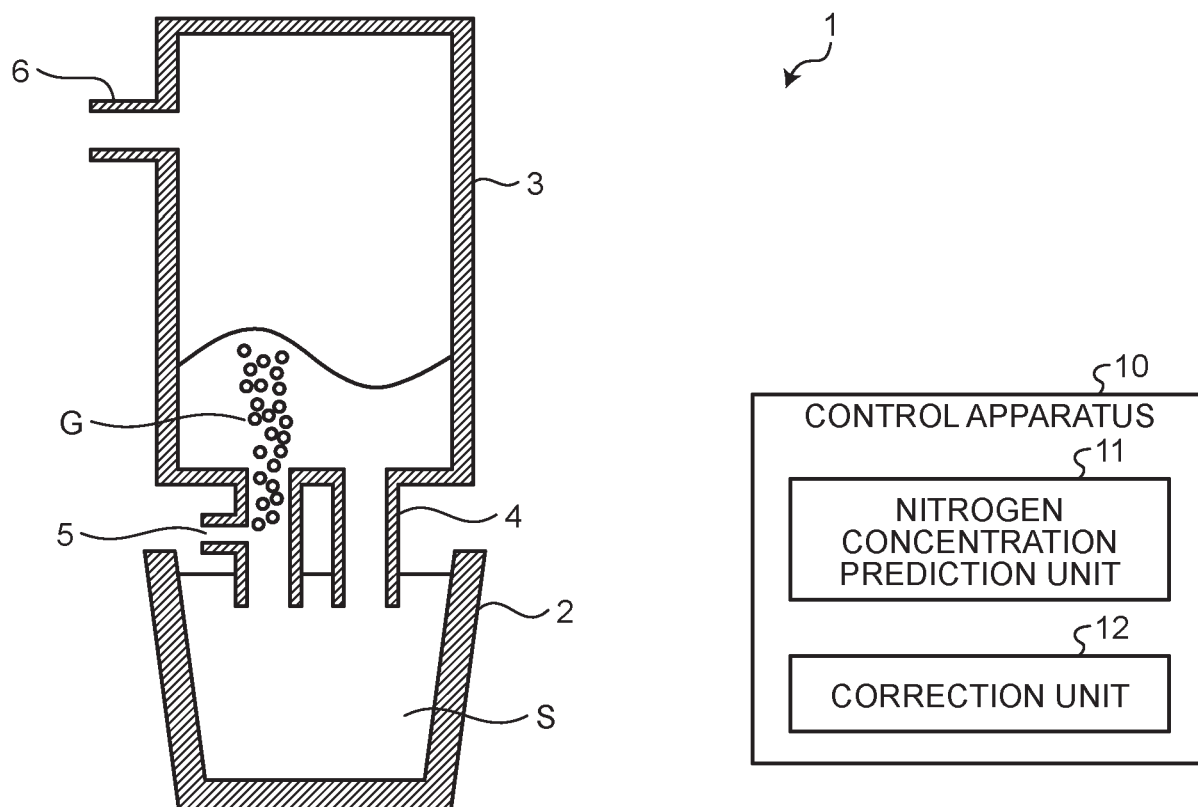
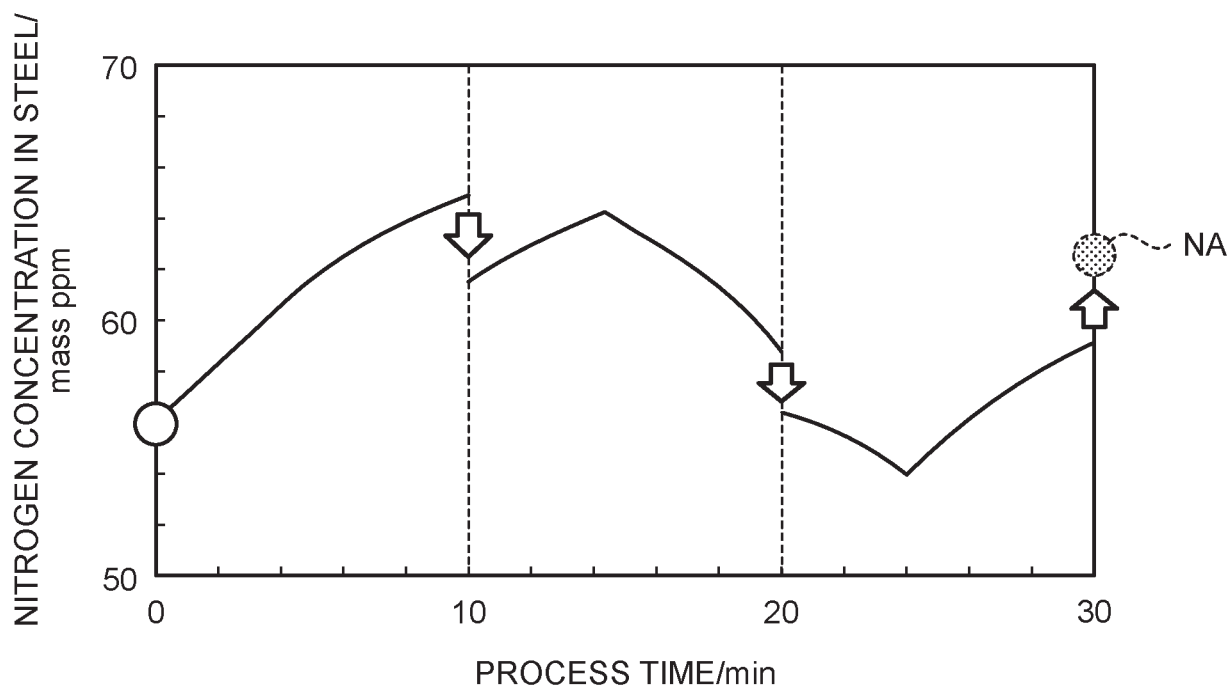
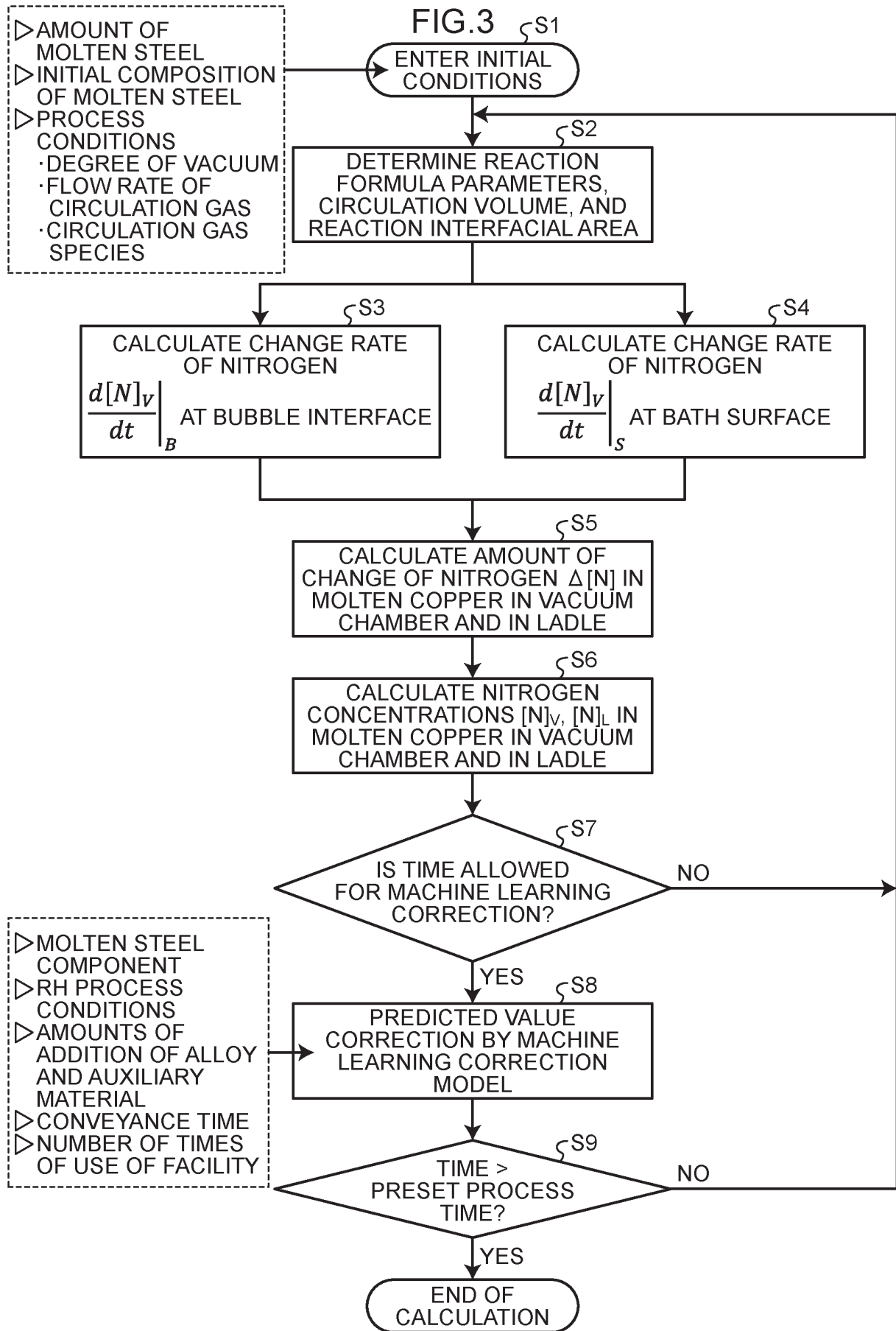


FIG.2





INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2024/041914

A. CLASSIFICATION OF SUBJECT MATTER

C21C 7/00(2006.01)i; **C21C 7/10**(2006.01)i
FI: C21C7/00 R; C21C7/10 P

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)

C21C7/00; C21C7/10

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 1971-2025
Registered utility model specifications of Japan 1996-2025
Published registered utility model applications of Japan 1994-2025

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.
A	CN 117076828 A (SHOUGANG GROUP CO., LTD.) 17 November 2023 (2023-11-17) claims, paragraphs [0083]-[0110]	1-6
A	CN 114689816 A (HUNAN HUAZHOI RIPPY STEEL CO., LTD.) 01 July 2022 (2022-07-01) claims	1-6
A	CN 113435114 A (MAANSHAN IRON & STEEL CO., LTD.) 24 September 2021 (2021-09-24) paragraphs [0008]-[0016]	1-6

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

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/JP2024/041914

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
CN	117076828	A	17 November 2023	(Family: none)	
CN	114689816	A	01 July 2022	(Family: none)	
CN	113435114	A	24 September 2021	(Family: none)	

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REFERENCES CITED IN THE DESCRIPTION

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