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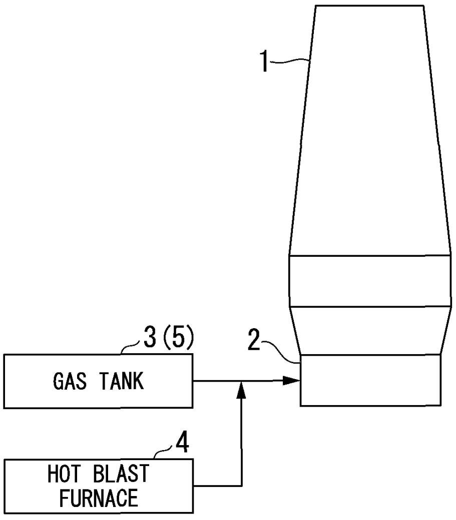
(54) BLAST FURNACE OPERATION METHOD

(57) According to a certain viewpoint of the present invention, there is provided a blast furnace operation method comprising blowing a high-concentration hydrogen-containing gas containing 80 mol% or more of hydrogen gas from a tuyere under: a condition in which a blowing temperature of the high-concentration hydrogen-containing gas is room temperature or higher and 300°C or lower and a gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 200 Nm^3/t or more and 500 Nm^3/t or less; a condition in which the blowing temperature of the high-concentration hydrogen-containing gas is higher than 300°C and 600°C or lower and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 145 Nm^3/t or more; a condition in which the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C and 900°C or lower and the gas volume of the high-concentration hydrogen-containing gas is 125 Nm^3/t or more, or the like.

FIG. 1



EP 4 067 510 A1

Description

[Technical Field of the Invention]

[0001] The present invention relates to a blast furnace operation method.

[0002] Priority is claimed on Japanese Patent Application No. 2019-216568, filed in Japan on November 29, 2019 and Japanese Patent Application No. 2020-092467, filed in Japan on May 27, 2020, the contents of which are incorporated herein by reference.

[Related Art]

[0003] In the steel industry, a blast furnace method is a mainstream steelmaking process. In the blast furnace method, iron-bearing materials for a blast furnace (raw materials including iron oxide; mainly sintered ores; hereinafter simply referred to as "iron-bearing materials") and coke are alternately charged in layers in the blast furnace from the top of the blast furnace, and hot blast is blown into the blast furnace from a tuyere of a lower part of the blast furnace. The hot blast reacts with pulverized coal blown together with the hot blast and the coke in the blast furnace such that a high-temperature reducing gas (here, mainly CO gas) is produced in the blast furnace. That is, the hot blast gasifies the coke and the pulverized coal in the blast furnace. The reducing gas rises in the blast furnace and reduces the iron-bearing materials while heating the iron-bearing materials. The iron-bearing materials are heated and reduced by the reducing gas while falling in the blast furnace. Next, the iron-bearing materials are melted and are dropped into the blast furnace while being further reduced by the coke. Finally, the iron-bearing materials are accumulated in a hearth as molten iron (pig iron) including about 5 mass% of carbon. The molten iron in the hearth is extracted from a tap hole and is provided for the next steelmaking process. Accordingly, in the blast furnace method, a carbon material such as coke or pulverized coal is used as a reducing material.

[0004] Meanwhile, in recent years, the prevention of global warming has been called for, and the reduction of carbon dioxide (CO_2 gas) emissions, which is one greenhouse gas, has become a social problem. As described above, in the blast furnace method, a carbon material is used as a reducing material. Thus, a large amount of CO_2 gas is generated. Accordingly, the steel industry is one of the main industries producing CO_2 gas emissions and needs to meet the demands of society. Specifically, further reduction in a reducing material ratio (the amount of a reducing material used per ton of molten iron) is urgently required in the blast furnace operation.

[0005] The reducing material has a function of heating charges inside the furnace as a heat source and a function of reducing the iron-bearing material in the furnace, and the reduction efficiency in the furnace needs to be increased in order to reduce the reducing material ratio. Reduction reactions in the furnace can be represented by various reaction formulae. Among these reduction reactions, a direct reduction reaction (reaction formula: $FeO + C \rightarrow Fe + Co$) by coke is an endothermic reaction accompanied by high endothermic heat. Accordingly, in order to reduce the reducing material ratio, it is important to suppress the occurrence of this reaction as much as possible. The direct reduction reaction occurs in a lower part of the blast furnace. Therefore, as long as the iron-bearing materials can be sufficiently reduced by a reducing gas such as CO or H_2 before the iron-bearing materials reach the furnace lower part, the iron-bearing materials that are a target of the direct reduction reaction can be reduced.

[0006] As the related art for solving the above-described problems, for example, as disclosed in Patent Documents 1 to 6, a technique of blowing a reducing gas (H2 gas, coke oven gas (COG), natural gas, city gas, or the like) together with hot blast from a tuyere to improve the reducing gas potential in the furnace is known. In a case where the reducing gas is a carbon-containing reducing gas (a reducing gas in which carbon atoms are contained in a molecular structure of the gas, for example, a hydrocarbon gas), the carbon atoms in the carbon-containing gas become CO gas in the blast furnace, which reduces the iron-bearing materials. In a case where the reducing gas is hydrogen gas (H2 gas), the hydrogen gas reduces the iron-bearing materials. Accordingly, the amount of the iron-bearing materials that are a target for the direct reduction reaction can be reduced. In addition, in the following description, unless particularly specified, "carbon" and "hydrogen" mean "carbon atom" and "hydrogen atom", respectively.

[Prior Art Document]

[Patent Document]

[0007]

[Patent Document 1] Japanese Patent No. 6019893
[Patent Document 2] Japanese Patent No. 5987773
[Patent Document 3] Japanese Patent No. 5050706

[Patent Document 4] Japanese Patent No. 5770124
[Patent Document 5] Japanese Patent No. 5315732
[Patent Document 6] Japanese Patent No. 5851828

[Disclosure of the Invention]

[Problems to be Solved by the Invention]

[0008] However, in the techniques disclosed in Patent Documents 1 to 6, the reducing gas volume blown from the tuyere is small, and the effect of reducing the CO_2 emissions is small.

[0009] Thus, the present invention has been made in view of the above problems, and an object of the present invention is to provide a new and improved blast furnace operation method capable of increasing the gas volume of a high-concentration hydrogen-containing gas blown from a tuyere as a reducing gas while maintaining a stable blast furnace operation, and further reducing the CO_2 emissions.

[Means for Solving the Problem]

[0010] In order to solve the above problems, according to a certain viewpoint of the present invention, there is provided a blast furnace operation method comprising blowing a high-concentration hydrogen-containing gas containing 80 mol% or more of hydrogen gas from a tuyere under: a condition in which a blowing temperature of the high-concentration hydrogen-containing gas is room temperature or higher and 300°C or lower and a gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 200 Nm^3/t or more and 500 Nm^3/t or less; a condition in which the blowing temperature of the high-concentration hydrogen-containing gas is higher than 300°C and 600°C or lower and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 145 Nm^3/t or more; a condition in which the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C and 900°C or lower and the gas volume of the high-concentration hydrogen-containing gas is 125 Nm^3/t or more; a condition in which the blowing temperature of the high-concentration hydrogen-containing gas is higher than 900°C and 1200°C or lower and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 110 Nm^3/t or more; or a condition in which the blowing temperature of the high-concentration hydrogen-containing gas is higher than 1200°C and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 100 Nm^3/t or more.

[0011] Here, the blowing temperature of the high-concentration hydrogen-containing gas may be room temperature or higher and 300°C or lower and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas may be 200 Nm^3/t or more and 300 Nm^3/t or less.

[0012] Here, the blowing temperature of the high-concentration hydrogen-containing gas may be higher than 300°C and 600°C or lower and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas may be 145 Nm^3/t or more and 600 Nm^3/t or less.

[0013] Additionally, the flame temperature may be 2050°C or lower.

[0014] Additionally, the flame temperature may be set to higher than 2050°C and 2150°C or lower.

[0015] Additionally, the flame temperature may be set to higher than 2150°C and 2250°C or lower.

[0016] Additionally, the blowing temperature of the high-concentration hydrogen-containing gas may be higher than 600°C and 1400°C or lower.

[0017] Additionally, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas may be 1000 Nm^3/t or less.

[0018] Additionally, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 400 Nm^3/t or more, a flame temperature may be set to 2050°C or lower.

[0019] According to another aspect of the present invention, there is provided a blast furnace operation method comprising obtaining a gas volume-carbon consumption parameter correlation, which is a correlation between a gas volume of hydrogen gas in a high-concentration hydrogen-containing gas and a carbon consumption parameter related to a carbon consumption amount when a blowing temperature of the high-concentration hydrogen-containing gas containing 80 mol% or more of the hydrogen gas is a predetermined value, in advance for each flame temperature; determining the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas at which the carbon consumption amount is reduced compared to that of a current operation, on the basis of the gas volume-carbon consumption parameter correlation; and blowing the high-concentration hydrogen-containing gas from the tuyere at the determined gas volume.

[0020] Additionally, the correlation between the hydrogen gas volume into the high-concentration hydrogen-containing gas and the carbon consumption parameter may be obtained for each blowing temperature of the high-concentration hydrogen-containing gas.

[0021] Additionally, a gas volume-pressure drop change correlation, which is a correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and a change amount of a pressure loss with respect to a base operation when the blowing temperature of the high-concentration hydrogen-containing gas is a predetermined value, may be obtained in advance for each flame temperature, and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas at which the carbon consumption amount is reduced compared to that of the current operation and the change amount of the pressure loss is a value within a predetermined range may be determined on the basis of the gas volume-carbon consumption parameter correlation and the gas volume-pressure drop change correlation.

[0022] Additionally, a gas volume-top gas temperature change amount correlation, which is a correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and a change amount of a top gas temperature with respect to a base operation when the blowing temperature of the high-concentration hydrogen-containing gas is a predetermined value, may be obtained in advance for each flame temperature, and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas at which the carbon consumption amount is reduced compared to that of the current operation and the change amount of the top gas temperature is a value within a predetermined range may be determined on the basis of the gas volume-carbon consumption parameter correlation and the gas volume-top gas temperature change amount correlation.

[Effects of the Invention]

[0023] As described above, according to the above viewpoint of the present invention, it is possible to increase the gas volume of the high-concentration hydrogen-containing gas blown from the tuyere as a reducing gas while maintaining a stable blast furnace operation, and further reduce the CO_2 emissions.

[Brief Description of the Drawings]

[0024]

FIG. 1 is a diagram for explaining a blowing temperature of a high-concentration hydrogen-containing gas.

FIG. 2 is a graph showing the correlation between the gas volume of pure hydrogen gas at room temperature and the reduction percentage Input ΔC of specific carbon consumption for each flame temperature Tf.

FIG. 3 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 300°C and the reduction percentage Input ΔC of the specific carbon consumption for each flame temperature Tf.

FIG. 4 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 350°C and the reduction percentage Input ΔC of the specific carbon consumption.

FIG. 5 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 600°C and the reduction percentage Input ΔC of the specific carbon consumption for each flame temperature Tf.

FIG. 6 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 650°C and the reduction percentage Input ΔC of the specific carbon consumption.

FIG. 7 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 900°C and the reduction percentage Input ΔC of the specific carbon consumption for each flame temperature Tf.

FIG. 8 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 950°C and the reduction percentage Input ΔC of the specific carbon consumption.

FIG. 9 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 1200°C and the reduction percentage Input ΔC of the specific carbon consumption for each flame temperature Tf.

FIG. 10 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 1250°C and the reduction percentage Input ΔC of the specific carbon consumption.

FIG. 11 is a graph showing the correlation between the gas volume of the pure hydrogen gas at room temperature or the gas volume of the hydrogen gas in an 80 mol% H2-20 mol% N_2 high-concentration hydrogen-containing gas at room temperature and the reduction percentage Input ΔC of the specific carbon consumption.

FIG. 12 is a graph showing the correlation between the gas volume of the pure hydrogen gas at room temperature and the change amount of pressure loss for each flame temperature Tf.

FIG. 13 is a graph showing the correlation between the gas volume of the pure hydrogen gas at room temperature and the change amount of a top gas temperature for each flame temperature Tf.

FIG. 14 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 1200°C and the change amount of pressure loss when the flame temperature Tf reaches 2100°C.

FIG. 15 is a graph showing the correlation between the blowing temperature of the pure hydrogen gas and the gas volume of pure hydrogen gas required to set the reduction percentage Input ΔC of specific carbon consumption to 10%.

FIG. 16 is a graph showing the correlation between the blowing temperature of the pure hydrogen gas and the gas volume of pure hydrogen gas required to set the reduction percentage Input ΔC of the specific carbon consumption to 20%.

[Embodiments of the Invention]

[0025] Preferred embodiments of the present invention will be described in detail below with reference to the accompanying drawings. In addition, in the present embodiment, a numerical range represented using "to" is a range including numerical values described before and after "to" as a lower limit and an upper limit. Additionally, the "reducing material ratio" is the total mass of a reducing material required to produce 1 ton of molten iron. Therefore, the reducing material ratio is basically the total mass of the coke and the pulverized coal required to produce 1 ton of molten iron, and the mass of a carbon-containing reducing gas in a high-concentration hydrogen-containing gas is treated as not included in the reducing material ratio. Additionally, the "specific carbon consumption (Input C)" is the carbon required to produce 1 ton of molten iron (that is, the carbon consumption amount per ton of molten iron). The "reduction percentage Input ΔC of specific carbon consumption" is the reduction percentage of specific carbon consumption to the base operation that is an operation in which the high-concentration hydrogen-containing gas is not blown. Assuming that the Input C of the base operation in units of kg/t is A and the Input C at the time of the operation in units of kg/t is B, the Input ΔC is expressed by the following formula.

$$\text{Input } \Delta C = (A\text{-}B)/A \times 100\ (\%)$$

[0026] The larger the reduction percentage Input ΔC of the specific carbon consumption, the smaller the reducing material ratio, and the more CO_2 emissions are reduced.

<1. Findings by the present inventor>

[0027] In order to solve the above problems, the present inventor has focused on the high-concentration hydrogen-containing gas as a reducing gas. Here, the high-concentration hydrogen-containing gas in the present embodiment is a gas containing 80 mol% or more of hydrogen gas (mol% of hydrogen gas with respect to the total amount of substances of all the gases constituting the high-concentration hydrogen-containing gas). The high-concentration hydrogen-containing gas may be pure hydrogen gas (gas having a hydrogen gas concentration of 100 mol%).

[0028] Further, the present inventors have focused on the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas (hereinafter, also simply referred to as the gas volume of hydrogen) and the blowing temperature of the high-concentration hydrogen-containing gas. The reduction reaction of an iron-bearing material by the hydrogen gas in the high-concentration hydrogen-containing gas is an endothermic reaction. In order to compensate for a temperature drop caused by the endothermic reaction, raising the blowing temperature of the hydrogen gas can be considered. However, it is extremely difficult to find the amount of drop in the temperature inside the furnace in a case where a large amount of the hydrogen gas in the high-concentration hydrogen-containing gas is blown in, and the degree of heat compensation required depending on the amount of decrease in the temperature inside the furnace. Therefore, detailed study of these has not been performed so far. The present inventors first performed a detailed study on the above matters. Specifically, finding the composition of various gases such as hydrogen gas and CO gas in the high-concentration hydrogen-containing gas and the reduction reaction rate of the high-concentration hydrogen-containing gas at various blowing temperatures, finding the effect of the temperature inside the furnace, which changes due to the reduction reaction heat of these gases, on the reduction reaction rate and the effect of the gas composition, which changes due to the reduction reaction, on the reduction reaction rate, and then finding the amounts of heat such that the reduction reaction rate does not decrease were performed for the entire furnace. For such a study, performance of multiple tests on an actual blast furnace machine, tests using an experimental device that can blow the gas inside the blast furnace under the conditions inside the blast furnace while simulating adiabatic conditions using a test blast furnace level device, and study performed by a simulation model are needed. The present inventors performed the above study using the simulation model, and as a result, found that an appropriate range of the gas volume is present for each blowing temperature.

[0029] That is, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is 600°C or lower, the reduction percentage Input ΔC of the specific carbon consumption does not simply increase with an increase in the gas volume of hydrogen gas in the high-concentration hydrogen-containing gas, but is relaxed and starts to decrease when the gas volume increases to some extent. Also, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas when the reduction percentage Input ΔC of the specific carbon consumption is relaxed and starts to decrease varies depending on the blowing temperature of the high-concentration hydrogen-containing gas. On the other hand, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C, the reduction percentage Input ΔC of the specific carbon consumption tends to increase with an increase in the gas volume. When the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas increases to some extent, the reduction percentage Input ΔC of the specific carbon consumption becomes, for example, 7% or more. Therefore, the CO_2 emissions can be significantly reduced by blowing the gas volume of the high-concentration hydrogen-containing gas in the blast furnace, which is determined according to the gas volume of hydrogen gas in this appropriate range. For example, as shown in examples described below, the reduction percentage Input ΔC of specific carbon consumption during the operation of the blast furnace can be set to 7% or more, and the CO_2 emissions can be significantly reduced. The present inventors came up with a blast furnace operation method according to the present embodiment on the basis of such knowledge. Hereinafter, the present embodiment will be described in detail.

<2. Composition of high-concentration hydrogen-containing gas>

[0030] In the blast furnace operation method according to the present embodiment, the high-concentration hydrogen-containing gas is blown from a tuyere. Thus, first, the composition of the high-concentration hydrogen-containing gas will be described. The high-concentration hydrogen-containing gas is a gas containing 80 mol% or more of hydrogen gas as described above. The high-concentration hydrogen-containing gas includes pure hydrogen gas. The high-concentration hydrogen-containing gas includes gas components other than the hydrogen gas, for example, the above-described carbon-containing reducing gas (for example, a hydrocarbon gas), CO gas, CO_2 gas, H_2O gas, N_2 gas, or the like. However, the total concentration of the other gases is less than 20 mol%.

[0031] Gases of which the total concentration of the other gas components is 20 mol% or more are not included in the high-concentration hydrogen-containing gas in the present embodiment. This is because the reduced amount of CO_2 gas decreases significantly in a case where the concentration of the other gases is 20 mol% or more. For example, since hydrocarbon gases, CO_2 gas, and H_2O gas among other gas components cause an endothermic reaction when the gases are decomposed at a tuyere tip, the reduction efficiency in the blast furnace decreases. For this reason, the amount of iron-bearing materials that reach a lower part of the blast furnace without being reduced increases. Therefore, the amount of direct reduction reaction by coke increases. Therefore, a large amount of the reducing material is required to maintain the temperature in the blast furnace, and the amount of CO_2 gas reduction decreases significantly. For example, in a case where COG (coke furnace gas) containing 50 mol% of hydrogen gas is blown into the blast furnace with a gas volume of 600 Nm^3/t, the hydrogen gas is blown into the blast furnace with a gas volume of 300 Nm^3/t. The effect of reducing the CO_2 emissions in this case is significantly inferior to that when the pure hydrogen gas is blown into the blast furnace with a gas volume of 300 Nm^3/t, and does not lead to a drastic reduction of the CO_2 emissions (for example, reduction percentage Input ΔC of specific carbon consumption ≥ 7%). In addition, as shown in the examples described below, in the example of the pure hydrogen gas at room temperature, the effect of reducing the CO_2 emissions is maximized when the gas volume is about 300 Nm^3/t.

<3. Blast furnace operation method>

[0032] Next, the blast furnace operation method according to the present embodiment will be described. In the blast furnace operation method according to the present embodiment, first, the blowing temperature of the high-concentration hydrogen-containing gas is determined within a range of room temperature or higher.

[0033] Here, the blowing temperature of the high-concentration hydrogen-containing gas (hereinafter, this may be simply referred to as "blowing temperature") will be described with reference to FIG. 1. FIG. 1 is a diagram for explaining the blowing temperature. The temperature of the high-concentration hydrogen-containing gas is regulated, for example, in a gas tank 3 including a heater 5. That is, the high-concentration hydrogen-containing gas is sent to the tuyere 2 for blowing hot blast provided at the lower part of the blast furnace 1 after being heated by the heater 5 in the gas tank 3 or while remaining unheated at room temperature. The high-concentration hydrogen-containing gas sent to the tuyere 2 can be blown into the blast furnace 1 from the tuyere 2. Specifically, the high-concentration hydrogen-containing gas sent to the tuyere 2 is mixed (merged) with the hot blast generated in a hot blast furnace 4 and then blown into the blast furnace 1 from the tuyere 2. The blowing temperature is the temperature of the high-concentration hydrogen-containing gas immediately before being mixed with the hot blast when the hot blast is blown into the blast furnace 1 from the tuyere 2. In actual operation (actual furnace), for example, since there is no temperature drop from the heater 5 that heats the high-concentration hydrogen-containing gas until the gas is blown into the blast furnace 1, the set temperature of the heater 5 can be set as the blowing temperature. Although the temperature of the high-concentration hydrogen-containing gas rises due to the mixing of the hot blast and the high-concentration hydrogen-containing gas, the temperature in this case is not the blowing temperature in the present embodiment. Additionally, although the blast temperature is described in Patent Document 1, the blast temperature in Patent Document 1 is different from the blowing temperature in the present embodiment.

[0034] As shown in the examples described below, the CO_2 emissions can be significantly reduced even in a case where the high-concentration hydrogen-containing gas is blown from the tuyere at room temperature without heating (see FIG. 2). FIG. 2 is a graph showing the correlation between the gas volume of the pure hydrogen gas at room temperature and the reduction percentage Input ΔC of the specific carbon consumption for each flame temperature Tf. This graph is obtained by blast furnace operation simulation. Details of the blast furnace operation simulation are described in the examples. However, here, a so-called "Blast Furnace Mathematical Model" Kouji TAKATANI, Takanobu INADA, Yutaka UJISAWA, "Three-dimensional Dynamic Simulator for Blast Furnace", ISIJ International, Vol. 39 (1999), No. 1, pp. 15 to 22 was used. In this blast furnace mathematical model, an internal region of the blast furnace is divided in a height direction, a radial direction, and a circumferential direction to define a plurality of meshes (small regions), and the behavior of each of the meshes is simulated. The simulation conditions were the same as in the examples described below. As shown in FIG. 2, in a case where the gas volume of the pure hydrogen gas at room temperature is 200 to 500 Nm^3/t, it is possible to set the reduction percentage Input ΔC of the specific carbon consumption to, for example, 7% or more. The reduction percentage Input ΔC of the specific carbon consumption is preferably 8% or more. In addition, "room temperature" in the present embodiment means an unheated state, and specifically, is a temperature of 5°C or higher and 35°C or lower.

[0035] Although details will be described below, when the blowing temperature is within a range of room temperature or higher, the reduction percentage Input ΔC of the specific carbon consumption to the same gas volume increases as the blowing temperature of the high-concentration hydrogen-containing gas is higher (see FIGS. 2 to 10). FIG. 3 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 300°C and the reduction percentage Input ΔC of the specific carbon consumption for each flame temperature Tf. FIG. 4 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 350°C and the reduction percentage Input ΔC of the specific carbon consumption. FIG. 5 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 600°C and the reduction percentage Input ΔC of the specific carbon consumption for each flame temperature Tf. FIG. 6 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 650°C and the reduction percentage Input ΔC of the specific carbon consumption. FIG. 7 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 900°C and the reduction percentage Input ΔC of the specific carbon consumption for each flame temperature Tf. FIG. 8 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 950°C and the reduction percentage Input ΔC of the specific carbon consumption. FIG. 9 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 1200°C and the reduction percentage Input ΔC of specific carbon consumption for each flame temperature Tf. FIG. 10 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 1250°C and the reduction percentage Input ΔC of the specific carbon consumption.

[0036] These graphs are obtained from the above-described blast furnace operation simulation. The details will be described in the examples. It can be seen that the reduction percentage Input ΔC of specific carbon consumption of FIGS. 3 to 10 is higher than the reduction percentage Input ΔC of the specific carbon consumption of FIG. 2. The higher the blowing temperature of the high-concentration hydrogen-containing gas, the higher the sensible heat of a Bosch gas (a mixed gas of nitrogen gas, hydrogen gas, and CO gas) generated in the blast furnace. Thus, it is considered that more reducing gas will reduce iron-bearing materials. That is, the reduction efficiency will become higher. For this reason, it is considered that a higher blowing temperature of the high-concentration hydrogen-containing gas will lead to a larger reduction percentage Input ΔC of the specific carbon consumption. Therefore, from the viewpoint of increasing the reduction percentage Input ΔC of the specific carbon consumption, it is preferable to raise the blowing temperature of the high-concentration hydrogen-containing gas. Specifically, it is preferable to determine the blowing temperature in a range of higher than 300°C, more preferably in a range of higher than 600°C, and more preferably in a range of higher than 900°C.

[0037] However, in order to raise the blowing temperature of the high-concentration hydrogen-containing gas to higher than 600°C, there is a case where large-scale equipment remodeling is required. For this reason, in a case where it is difficult to set the blowing temperature of the high-concentration hydrogen-containing gas to higher than 600°C with existing equipment, the blowing temperature of the high-concentration hydrogen-containing gas may be determined within a range of room temperature to 600°C. On the other hand, in a case where the blowing temperature of the high-concentration hydrogen-containing gas can be increased to higher than 600°C with the existing equipment (or by re-modeling the existing equipment), the blowing temperature of the high-concentration hydrogen-containing gas may be determined within a range of higher than 600°C.

[0038] Next, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is determined. Here, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is the flow rate per ton of molten iron of hydrogen gas in the high-concentration hydrogen-containing gas blown into the blast furnace from the tuyere, and the unit is Nm^3/t. When the high-concentration hydrogen-containing gas is the pure hydrogen gas, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is equal to the gas volume of the high-concentration hydrogen-containing gas. When the high-concentration hydrogen-containing gas is a mixed gas containing gases other than the hydrogen gas, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is the amount obtained by multiplying the gas volume of the high-concentration hydrogen-containing gas in units of mol% by the ratio of the hydrogen gas. In the actual operation, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is calculated from the value indicated by a flow meter provided at a discharge port of a high-concentration hydrogen-containing gas supply source (for example, a gas tank) and the ratio of the hydrogen gas in the high-concentration hydrogen-containing gas in units of mol%.

[0039] In the present embodiment, the gas volume is determined by classifying cases at the blowing temperature of the high-concentration hydrogen-containing gas. Specifically, in a case where the blowing temperature is room temperature to 300°C, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is determined within a range of 200 to 500 Nm^3/t. On the other hand, in a case where the blowing temperature is higher than 300°C and 600°C or lower, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is determined within a range of 145 Nm^3/t or more. In a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C and 900°C or lower, the gas volume of the high-concentration hydrogen-containing gas is determined within a range of 125 Nm^3/t or more. In a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 900°C and 1200°C or lower, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is determined within a range of 110 Nm^3/t or more. In a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 1200°C, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is determined within a range of 100 Nm^3/t or more.

[0040] The reason why cases are classified according to the blowing temperature in this way is that a preferred gas volume varies slightly depending on the blowing temperature. In addition, in the following description, a case where the high-concentration hydrogen-containing gas is the pure hydrogen gas will be described as an example. However, as shown in Example 1-2 described below, even in a case where the high-concentration hydrogen-containing gas contains a gas component other than the hydrogen gas, the correlation between the blowing temperature of the high-concentration hydrogen-containing gas and the preferred gas volume does not change.

[0041] As shown in FIGS. 2 and 3, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is from room temperature to 300°C, the reduction percentage Input ΔC of the specific carbon consumption increases when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is increased from 0 in the base operation. Then, when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas reaches about 300 Nm^3/t, the reduction percentage Input ΔC of the specific carbon consumption reaches a peak, and when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas further increases, the reduction percentage Input ΔC of the specific carbon consumption starts to decrease. Then, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is in a range of 200 to 500 Nm^3/t, it is possible to set the reduction percentage Input ΔC of the specific carbon consumption to 7% or more. In addition, in a case where the high-concentration hydrogen-containing gas is pure hydrogen gas, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is the gas volume of the high-concentration hydrogen-containing gas. However, in a case where the high-concentration hydrogen-containing gas includes a gas component other than the hydrogen gas, this value is the amount obtained by multiplying the gas volume of the high-concentration hydrogen-containing gas by the ratio of the hydrogen gas (mol%).

[0042] The reduction reaction of the iron-bearing materials with the hydrogen gas (that is, the hydrogen reduction reaction) is an endothermic reaction. For this reason, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas exceeds 300 Nm^3/t, it is considered that such an endothermic reaction occurs frequently in the furnace and the temperature inside the furnace drops. Also, such a decrease in the temperature inside the furnace is considered to reduce the reduction efficiency of the reducing gas containing hydrogen gas. In order to prevent such a decrease in reduction efficiency, it is necessary to increase the reducing material ratio to perform the operation. For this reason, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas exceeds 300 Nm^3/t, the reduction percentage Input ΔC of the specific carbon consumption starts to decrease. Therefore, in a case where the blowing temperature is room temperature to 300°C, it is preferable to determine the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas within a range of 200 to 400 Nm^3/t, and it is more preferable to determine the gas volume within a range of 200 to 300 Nm^3/t. In this case, it is possible to set the reduction percentage Input ΔC of the specific carbon consumption to 8% or more.

[0043] As shown in FIGS. 4 and 5, even in a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 300°C and 600°C or lower, the reduction percentage Input ΔC of the specific carbon consumption increases when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is increased from 0 Nm^3/t Nm in the base operation. Then, when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 145 Nm^3/t or more, the reduction percentage Input ΔC of the specific carbon consumption becomes 7% or more. In a case where the blowing temperature of the high-concentration hydrogen-containing gas is 600°C, as shown in FIG. 5, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is about 600 Nm^3/t, and the reduction percentage Input ΔC of the specific carbon consumption reaches saturation. Then, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is 350°C, as shown in FIG. 4, when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas reaches about 300 Nm^3/t, the reduction percentage Input ΔC of the specific carbon consumption reaches a peak, and when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas further increases, the reduction percentage Input ΔC of the specific carbon consumption starts to decrease.

[0044] In addition, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is 350°C, it is difficult to maintain the tuyere tip temperature Tf at 2200°C when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas exceeds 600 Nm^3/t. In the related-art blast furnace operation, the flame temperature Tf is often set to about 2200°C, and in a case where it is difficult to maintain the flame temperature Tf at 2200°C, the operation conditions of the related-art blast furnace operation will be changed.

[0045] The reason why the reduction percentage Input ΔC of the specific carbon consumption starts to decrease in a case where the blowing temperature of the high-concentration hydrogen-containing gas is 350°C is the same as above. In a case where the blowing temperature of the high-concentration hydrogen-containing gas is 600°C, the reduction percentage Input ΔC of the specific carbon consumption does not start to decrease in a range of the gas volume up to 700 Nm^3/t. However, when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is about 600 Nm^3/t, the effect of reducing the specific carbon consumption reaches saturation. In a case where the blowing temperature is higher than 350°C and 600°C or lower, the sensible heat of the Bosch gas is larger. Therefore, since the influence of endothermic heat due to the hydrogen reduction reaction is reduced, the temperature inside the furnace is considered unlikely to drop even if more hydrogen gas is blown than in the above case. Therefore, it is considered that even when a large amount of hydrogen gas is blown into the blast furnace, the temperature inside the furnace does not easily decrease and the reduction efficiency is unlikely to decrease. For this reason, the reduction percentage Input ΔC of the specific carbon consumption is considered to have reached saturation. Moreover, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 300 to 600 Nm^3/t, the reduction percentage Input ΔC of the specific carbon consumption is 10% or more.

[0046] As shown in FIGS. 6 and 7, even in a case where the blowing temperature is higher than 600°C and 900°C or lower, the reduction percentage Input ΔC of the specific carbon consumption increases when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is increased from 0 Nm^3/t in the base operation. Then, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is within a range of 125 Nm^3/t or more, the reduction percentage Input ΔC of the specific carbon consumption is 7% or more. In particular, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is within a range of 180 Nm^3/t or more, the reduction percentage Input ΔC of the specific carbon consumption is 10% or more. Moreover, as the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas increases, the increase rate of the reduction percentage Input ΔC of the specific carbon consumption (increase amount of the reduction percentage Input ΔC of the specific carbon consumption to the unit increase amount of the gas volume) decreases. However, the reduction percentage Input ΔC of the specific carbon consumption does not start to decrease. This behavior is clearly different from the case where the blowing temperature of the high-concentration hydrogen-containing gas is 600°C or lower. FIG. 7 is a graph showing the correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and the reduction percentage Input ΔC of the specific carbon consumption in a case where the blowing temperature of the high-concentration hydrogen-containing gas (here, the pure hydrogen gas) is 900°C. The same tendency as in FIG. 7 was observed even in a case where the blowing temperature of the high-concentration hydrogen-containing gas was 650°C. For example, as shown in FIG. 6, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is 650°C and the gas volume of the high-concentration hydrogen-containing gas is 125 Nm^3/t or more, the reduction percentage Input ΔC the specific carbon consumption is 7.0% or more.

[0047] As described above, since the reduction reaction caused by the hydrogen gas is an endothermic reaction, when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas increases to some extent, the reduction percentage Input ΔC of the specific carbon consumption starts to decrease. However, if the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C, the sensible heat of the Bosch gas generated in the blast furnace becomes extremely high. Thus, the reaction heat required for the reduction reaction can be covered. For this reason, it is considered that even when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas increases, the reduction percentage Input ΔC of the specific carbon consumption does not start to decrease but continues to increase. Such behavior is observed in a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C. Therefore, from the viewpoint of further increasing the reduction percentage Input ΔC of the specific carbon consumption, the upper limit of the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is not separately set. However, as the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas increases, the increase rate of the reduction percentage Input ΔC of the specific carbon consumption decreases. Therefore, it is assumed that the effect of reducing the specific carbon consumption reaches a peak with a certain gas volume. The gas volume in this case is assumed to be approximately 1000 Nm^3/t. Therefore, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas may be 1000 Nm^3/t or less.

[0048] As shown in FIGS. 8 and 9, even in a case where the blowing temperature is higher than 900°C and 1200°C or lower, the reduction percentage Input ΔC of the specific carbon consumption increases when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is increased from 0 Nm^3/t Nm in the base operation. Then, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is within a range of 110 Nm^3/t or more, the reduction percentage Input ΔC of the specific carbon consumption is 7% or more. In particular, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is within a range of 150 Nm^3/t or more, the reduction percentage Input ΔC of the specific carbon consumption is 10% or more. Moreover, similar to the case where the blowing temperature of the high-concentration hydrogen-containing gas becomes higher than 600°C and 900°C or lower, as the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas increases, the increase rate of the reduction percentage Input ΔC of the specific carbon consumption decreases. However, the reduction percentage Input ΔC of the specific carbon consumption does not start to decrease. FIG. 9 is a graph showing the correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and the reduction percentage Input ΔC of the specific carbon consumption in a case where the blowing temperature of the high-concentration hydrogen-containing gas (here, pure hydrogen gas) is 1200°C. The same tendency as in FIG. 9 was observed even in a case where the blowing temperature of the high-concentration hydrogen-containing gas was 950°C. For example, as shown in FIG. 8, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is 950°C and the gas volume of the high-concentration hydrogen-containing gas is 110 Nm^3/t or more, the specific carbon consumption reduction percentage Input ΔC is 7.0% or more.

[0049] Therefore, from the viewpoint of further increasing the reduction percentage Input ΔC of the specific carbon consumption, the upper limit of the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is not separately set. However, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is about 1000 Nm^3/t, it is assumed that the effect of reducing the specific carbon consumption reaches a peak. Therefore, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas may be 1000 Nm^3/t or less.

[0050] In addition, according to the blast furnace operation simulation, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is 1200°C and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 800 Nm^3/t or more, the gas volume of the pulverized coal becomes 0, and it is possible to further reduce the specific carbon consumption by reducing a coke ratio. Generally, in the blast furnace operation, a decrease in the coke ratio causes an increase in the pressure loss, resulting in unstable operation. Here, the pressure loss is a difference between the pressure at the tuyere tip (the outlet of the tuyere), in other words, the pressure inside the furnace at an outlet of the tuyere and the pressure at the top of the furnace, and a value excluding the pipe pressure loss from a blower to the tuyere tip. In the actual operation, the pressure loss is measured by a pressure gauge installed on a furnace wall portion. However, as shown in FIG. 14, in the blast furnace operation under the high hydrogen concentration condition as in the present embodiment, the gas viscosity and the gas density in the furnace decrease significantly. Therefore, the concern about an increase in the pressure loss when the coke ratio is reduced is resolved, and the pressure loss is such that there is no problem with stable operation in the actual operation. In addition, FIG. 14 is a graph showing the correlation between the gas volume of the pure hydrogen gas at 1200°C and the change amount of the pressure loss inside the furnace when the flame temperature reaches 2100°C, which is obtained by the blast furnace operation simulation. The pressure loss in normal operation is about 85 kPa as a standard. According to FIG. 14, it can be seen that the pressure loss is less than 85 kPa under the operation conditions of the present embodiment.

[0051] As shown in FIG. 10, even in a case where the blowing temperature is higher than 1200°C, the reduction percentage Input ΔC of the specific carbon consumption increases when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is increased from 0 Nm^3/t Nm in the base operation. Then, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is within a range of 100 Nm^3/t or more, the reduction percentage Input ΔC of the specific carbon consumption is 7% or more. Moreover, similar to the case where the blowing temperature of the high-concentration hydrogen-containing gas becomes higher than 600°C and 900°C or lower, as the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas increases, the increase rate of the reduction percentage Input ΔC of the specific carbon consumption decreases. However, the reduction percentage Input ΔC of the specific carbon consumption does not start to decrease. Therefore, from the viewpoint of further increasing the reduction percentage Input ΔC of the specific carbon consumption, the upper limit of the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is not separately set. However, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is about 1000 Nm^3/t, it is assumed that the effect of reducing the specific carbon consumption reaches a peak. Therefore, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas may be 1000 Nm^3/t or less.

[0052] The upper limit of the blowing temperature is not particularly limited as long as the environment allows the blowing temperature of the high-concentration hydrogen-containing gas to exceed 600°C. However, as shown in FIGS. 15 and 16, the effect of reducing the specific carbon consumption is almost unchanged in a range where the blowing temperature of the high-concentration hydrogen-containing gas is in a range of higher than 1200°C to about 1400°C. In addition, FIGS. 15 and 16 are graphs showing the correlation between the blowing temperature of the pure hydrogen gas and the gas volume of the pure hydrogen gas required to set the reduction percentage Input ΔC of the specific carbon consumption to 10% or 20%. The flame temperature Tf was set to 2100°C. These graphs are obtained by organizing the correlation between FIGS. 2 to 10 by the correlation of the blowing temperature of the pure hydrogen gas and the gas volume of the pure hydrogen gas required to set the reduction percentage Input ΔC of the specific carbon consumption to 10% or 20%. Therefore, the blowing temperature of the high-concentration hydrogen-containing gas may be 1400°C or lower. That is, the blowing temperature of the high-concentration hydrogen-containing gas may be, for example, higher than 600°C and 1400°C or lower.

[0053] Next, the high-concentration hydrogen-containing gas is blown from the tuyere at the determined blowing temperature and gas volume. Accordingly, the reduction percentage Input ΔC of the specific carbon consumption can be set to, for example, 7% or more, and the CO_2 emissions can be significantly reduced. In addition, the tuyere for blowing the high-concentration hydrogen-containing gas is, for example, a tuyere for blowing hot blast provided at the lower part of the furnace. The present embodiment is described based on the premise that the high-concentration hydrogen-containing gas is blown from the tuyere for blowing hot blast. However, the tuyere for blowing the high-concentration hydrogen-containing gas is not limited to this. Another example of the tuyere is so-called shaft tuyeres provided on a shaft portion. The high-concentration hydrogen-containing gas may be blown into the blast furnace from any of these tuyeres or may be blown into the blast furnace from both tuyeres. In a case where the high-concentration hydrogen-containing gas is blown into the blast furnace from a plurality of tuyeres, the total gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas blown from each tuyere matches the above-determined gas volume.

[0054] In addition, by appropriately setting the hydrogen gas blowing temperature, the gas volume, the flame temperature Tf, and the like under the conditions of the present embodiment, the operation of appropriately maintaining the top gas temperature is possible. For this reason, it is unnecessary to blow in the preheated gas or preheat the charges inside the furnace, which is performed to maintain the top gas temperature, but these may be separately performed.

<4. Modification examples>

(4-1. Modification Example 1)

[0055] Hereinafter, various modification examples of the blast furnace operation method will be described. In Modification Example 1, the flame temperature Tf is maintained at 2050°C or lower. Here, the flame temperature is an in-furnace temperature in a tip end portion of the tuyere on the inside of the furnace, and will also be referred to as "tuyere tip temperature Tf". In the actual operation, the flame temperature Tf is calculated as a tuyere tip theoretical combustion temperature according to a Lamm equation described in "Ironmaking Handbook" (Chijinshokan Co., Ltd.), Akitoshi SHIGEMI.

[0056] As shown in FIGS. 2, 3, 5, 7, and 9, the reduction percentage Input ΔC of the specific carbon consumption in a case where the flame temperature Tf is 2050°C or lower (2000°C in FIGS. 2, 3, 5, 7, and 9) is larger than the reduction percentage Input ΔC of the specific carbon consumption in a case where the flame temperature Tf is higher than 2050°C (2100°C and 2200°C in FIGS. 2, 3, 5, 7, and 9). Thus, in Modification Example 1, the flame temperature Tf is maintained at 2050°C or lower. Accordingly, the reduction percentage Input ΔC of the specific carbon consumption can be further increased. In addition, as shown in FIGS. 7 and 9, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C and in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 400 Nm^3/t or more, this tendency appears remarkably. Therefore, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 400 Nm^3/t or more, the flame temperature Tf may be set to 2050°C or lower.

[0057] Here, since the blowing temperature of the high-concentration hydrogen-containing gas is lower than that of the hot blast, the flame temperature Tf is lowered by blowing the high-concentration hydrogen-containing gas in the blast furnace. In order to set the flame temperature Tf to a desired temperature, that is, to increase the flame temperature Tf, it is necessary to increase the oxygen enrichment ratio to perform the operation. Here, the hot blast blown into the blast furnace is a gas including air. The hot blast may include hygroscopic moisture and enriched oxygen in addition to air. The oxygen enrichment ratio is roughly the volume ratio of oxygen in the hot blast to the total volume of the hot blast, and "oxygen enrichment ratio (%) = {(blast volume (flow rate) [Nm^3/min] × 0.21 + amount of enriched oxygen [Nm^3/min] / (blast volume [Nm^3/min] + amount of enriched oxygen [Nm^3/min])} × 100 -21". In the actual operation, the oxygen enrichment ratio is adjusted by changing the flow rate of enriched oxygen in units of Nm^3/t and the flow rate of air without changing the flow rate of oxygen, which is the total flow rate of the enriched oxygen in units of Nm^3/t and oxygen in the hot blast. This is to keep the tapped iron ratio (daily tapped iron amount per m^3 volume inside the furnace) as constant as possible. Therefore, when the oxygen enrichment ratio increases, the flow rate of hot blast decreases. As a result, the amount of the Bosch gas decreases.

[0058] Therefore, as the flame temperature Tf is higher, the amount of the Bosch gas decreases. Then, when the amount of the Bosch gas decreases, the sensible heat of the Bosch gas decreases. Therefore, the temperature inside the furnace tends to decrease due to the endothermic heat generated by the hydrogen reduction reaction. Then, in order to prevent such a decrease in the temperature inside the furnace, it is necessary to perform an operation in which the reducing material ratio is increased. For this reason, it is considered that the reduction percentage Input ΔC of the specific carbon consumption in a case where the flame temperature Tf is 2050°C or lower is larger than the reduction percentage Input ΔC of the specific carbon consumption in a case where the flame temperature Tf is larger than 2050°C.

[0059] In addition, from the viewpoint of heat transfer to the molten iron and pulverized coal combustibility, the flame temperature Tf is preferably 2000°C or higher. However, if the reduction percentage Input ΔC of the specific carbon consumption can be sufficiently large and the pulverized coal ratio (the pulverized coal used per ton of molten iron) can be sufficiently lowered, the flame temperature Tf may be lower than 2000°C. For example, if the reduction percentage Input ΔC of the specific carbon consumption can be maintained even if the flame temperature Tf is lower than 2000°C and a stable operation is possible, the flame temperature Tf may be set to lower than 2000°C. In this respect, for example, as described above, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is 1200°C and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 800 Nm^3/t or more, the gas volume of the pulverized coal is 0 (that is, the pulverized coal ratio is 0). In this case, since it is not necessary to consider the combustion of the pulverized coal, the reduction percentage Input ΔC of the specific carbon consumption can be maintained even when the flame temperature Tf is lower than 2000°C, and a stable operation becomes possible. Therefore, the flame temperature Tf can be set to lower than 2000°C. That is, if the gas volume of the pulverized coal can be set to 0 as a result of raising the blowing temperature of the high-concentration hydrogen-containing gas and increasing the gas volume, the flame temperature Tf may be set to lower than 2000°C.

(4-2. Modification Example 2)

[0060] In Modification Example 2, the flame temperature Tf is maintained higher than 2050°C and lower than 2150°C. According to Modification Example 1, the reduction percentage Input ΔC of the specific carbon consumption can be increased by setting the flame temperature Tf to 2050°C or lower. On the other hand, when the flame temperature Tf decreases, there is a possibility of the combustion rate of the pulverized coal decreasing. That is, when the flame temperature Tf decreases, the pulverized coal is unlikely to combust. In a case where the pulverized coal is flame-retardant or in a case where the operation is performed by increasing the pulverized coal ratio, the possibility of the combustion rate of the pulverized coal decreasing is further increased. When the combustion rate of the pulverized coal decreases, the temperature inside the furnace decreases. Thus, it may be necessary to perform an operation in which the reducing material ratio is increased accordingly. From this point of view, in Modification Example 2, the flame temperature Tf is maintained higher than 2050°C and lower than 2150°C. Accordingly, the combustion rate of the pulverized coal can be maintained, and a decrease in the temperature inside the furnace can be suppressed.

(4-3. Modification Example 3)

[0061] In Modification Example 3, the flame temperature Tf is maintained higher than 2150°C. In the related-art blast furnace operation, the flame temperature Tf is often set to about 2200°C. Therefore, by setting the flame temperature Tf to higher than 2150°C, the operation can be performed without significantly changing the operation conditions from the related-art blast furnace operation. In addition, from the viewpoint of protecting the tuyere equipment, the flame temperature Tf is preferably 2250°C or lower.

(4-4. Modification Example 4)

[0062] As shown in FIGS. 2 to 10, there is a certain correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and the reduction percentage Input ΔC of the specific carbon consumption. Thus, in Modification Example 4, a gas volume-specific carbon consumption reduction percentage correlation, which is the correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and the reduction percentage Input ΔC of the specific carbon consumption, is obtained in advance.

[0063] For example, the reduction percentage Input ΔC of the specific carbon consumption for each of several gas volumes is obtained by the blast furnace operation simulation in which the current blast furnace operation including the blowing temperature of the high-concentration hydrogen-containing gas is reflected. The specific method may be the same as that of the examples described below.

[0064] Next, the values obtained by the above method are plotted on a plane where the horizontal axis is the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas in units of Nm^3/t and the vertical axis is the reduction percentage Input ΔC(%) of the specific carbon consumption. Next, the approximation curve from these plots may be obtained by, for example, the least squares method, and the approximation curve, more specifically, a relational expression showing the approximation curve, may be used as the above-described gas volume-specific carbon consumption reduction percentage correlation. It is preferable to obtain the gas volume and the specific carbon consumption reduction percentage correlation for each flame temperature Tf.

[0065] Next, the gas volume at which the reduction percentage Input ΔC of the specific carbon consumption is larger than that of the current operation, that is, the gas volume at which the carbon consumption amount is reduced, is determined on the basis of the gas volume-specific carbon consumption reduction percentage correlation obtained above. Next, the high-concentration hydrogen-containing gas is blown from the tuyere at the determined gas volume. Accordingly, the reduction percentage Input ΔC of the specific carbon consumption can be more reliably increased.

[0066] Here, it is preferable to obtain the gas volume-specific carbon consumption reduction percentage correlation in advance for each blowing temperature of the high-concentration hydrogen-containing gas. Accordingly, even in a case where the blowing temperature fluctuates, the desired gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas can be easily determined. That is, even in a case where the blowing temperature fluctuates, it is possible to easily determine the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas in which the reduction percentage Input ΔC of the specific carbon consumption becomes large.

(4-5. Modification Example 5)

[0067] FIG. 12 is a graph showing, for each flame temperature Tf, the correlation between the gas volume of the pure hydrogen gas at room temperature in units of Nm^3/t and the change amount of the pressure loss in units of kPa with respect to the base operation, which is an operation in which the high-concentration hydrogen-containing gas is not blown. This graph is obtained from a blast furnace operation simulation. The details will be described in the examples. Here, the pressure loss is a difference between the pressure at the tuyere tip (the outlet of the tuyere), in other words, the pressure inside the furnace at an outlet of the tuyere and the pressure at the top of the furnace, and a value excluding the pipe pressure loss from a blower to the tuyere tip. In the actual operation, the pressure loss is measured by a pressure gauge installed on a furnace wall portion. The change amount of the pressure loss with respect to the base operation is a value obtained by subtracting the pressure loss during the base operation from the pressure loss during a certain operation. It is preferable that the pressure loss be almost the same as that of the base operation or a value lower than that of the base operation from the viewpoint of the restriction of the blast pressure, the prevention of blow-by, and the like. FIG. 12 shows the above correlation in a case where the pure hydrogen gas at room temperature is used. The above correlation can also be obtained in a case where the high-concentration hydrogen-containing gas other than the pure hydrogen gas is used. Additionally, even when the blowing temperature of the high-concentration hydrogen-containing gas is higher than room temperature, the above correlation can be obtained.

[0068] As is clear from FIG. 12, there is a certain correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and the change amount of the pressure loss. For example, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is increased, the flame temperature Tf decreases as described above. In order to set the flame temperature to a desired temperature, it is necessary to increase the oxygen enrichment ratio to perform the operation. In the actual operation, the oxygen enrichment ratio is adjusted while the tapped iron amount is kept at a predetermined amount by changing the flow rate of enriched oxygen in units of Nm^3/t and the flow rate of air without changing the flow rate of oxygen, which is the total flow rate of the enriched oxygen and oxygen in the hot blast in units of Nm^3/t. Therefore, when the oxygen enrichment ratio increases, the flow rate of hot blast decreases. As a result, the amount of the Bosch gas decreases. In other words, in a case where the flame temperature Tf is low, the amount of the Bosch gas increases. As a result, there is a possibility of the pressure loss being larger than that of the base operation. However, when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is further increased, the gas viscosity and gas density of the gas in the furnace are lowered, and the pressure loss is reduced. Then, the decrease in pressure loss caused by the decrease in gas viscosity and gas density offsets the increase in the pressure loss caused by the increase in the amount of the Bosch gas, and as a result, the pressure loss decreases.

[0069] In Modification Example 5, first, the gas volume-specific carbon consumption reduction percentage correlation is obtained in advance similar to Modification Example 4. Moreover, a gas volume-pressure drop change correlation, which is the correlation between the gas volume and the change amount of the pressure loss with respect to the base operation, is obtained.

[0070] For example, the change amount of the pressure loss for each of several gas volumes is obtained by the blast furnace operation simulation in which the current blast furnace operation including the blowing temperature of the high-concentration hydrogen-containing gas is reflected. The specific method may be the same as that of the examples described below.

[0071] Next, the values obtained by the above method are plotted on a plane where the horizontal axis is the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas in units of Nm^3/t and the vertical axis is Δ pressure loss that is the change amount of the pressure loss in units of kPa. Next, the approximation curve from these plots may be obtained by, for example, the least squares method, and the approximation curve (more specifically, a relational expression showing the approximation curve) may be used as the above-described gas volume-pressure drop change correlation. The gas volume-pressure drop change correlation is preferably obtained for each flame temperature Tf.

[0072] Next, the reduction percentage Input ΔC of the specific carbon consumption is larger than that of the current operation, that is, the carbon consumption amount is reduced and the gas volume in which the change amount of the pressure loss is a value within a predetermined range is determined on the basis of the gas volume-specific carbon consumption reduction percentage correlation and the gas volume-pressure drop change correlation. Here, the predetermined range is, for example, about -50 to +5 kPa, but is not limited to this. Next, the high-concentration hydrogen-containing gas is blown from the tuyere at the determined gas volume. Accordingly, the reduction percentage Input ΔC of the specific carbon consumption can be more reliably increased while the change amount of the pressure loss is set to a value within a predetermined range.

(4-6. Modification Example 6)

[0073] FIG. 13 is a graph showing the correlation between the gas volume of the pure hydrogen gas in units of Nm^3/t at room temperature and the change amount of the top gas temperature with respect to the base operation in units of °C for each flame temperature Tf. This graph is obtained from a blast furnace operation simulation. The details will be described in the examples. Here, the top gas temperature is the temperature of the furnace top gas (mainly CO_2, N_2, unreacted CO, or the like) discharged from the top of the blast furnace, and in the actual operation, is measured by a thermometer installed on a riser tube or the like. The change amount of the top gas temperature with respect to the base operation is a value obtained by subtracting the top gas temperature during the base operation from the top gas temperature during a certain operation. The top gas temperature is preferably almost the same as that of the base operation from the viewpoint of restrictions on furnace top equipment and efficient operation, and as an example, is preferably within a range of about ± 20°C from the top gas temperature of the base operation. FIG. 13 shows the above correlation in a case where the pure hydrogen gas at room temperature is used The above correlation can also be obtained in a case where the high-concentration hydrogen-containing gas other than the pure hydrogen gas is used. Additionally, even when the blowing temperature of the high-concentration hydrogen-containing gas is higher than room temperature, the above correlation can be obtained.

[0074] As is clear from FIG. 13, there is a certain correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and the change amount of the top gas temperature. For example, in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is increased, the flame temperature Tf decreases as described above. In order to set the flame temperature Tf to a desired temperature, it is necessary to increase the oxygen enrichment ratio to perform the operation. In the actual operation, the oxygen enrichment ratio is adjusted by changing the flow rate of air in units of Nm^3/t without changing the flow rate of oxygen in units of Nm^3/t. Therefore, when the oxygen enrichment ratio increases, the flow rate of hot blast decreases. As a result, the amount of the Bosch gas decreases. In other words, when the flame temperature Tf rises, the amount of the Bosch gas decreases. For this reason, a heat flow ratio expressed by (heat capacity of charges inside furnace falling per unit time)/(heat capacity of Bosch gas rising per unit time) increases. As a result, the temperature of the gas inside the furnace that rises inside the furnace tends to decrease, and as a result, the top gas temperature tends to decrease. As a result, there is a possibility of the top gas temperature being lower than that of the base operation. However, when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is further increased, the temperature inside the furnace drops due to the endothermic reaction as described above with approximately 300 Nm^3/t as a boundary, and the reduction efficiency begins to decrease. In order to prevent such a decrease in reduction efficiency, the operation is performed by increasing the reducing material ratio. However, when the reducing material ratio is increased, the amount of heat input into the furnace increases and the top gas temperature tends to rise. Therefore, the top gas temperature starts to increase.

[0075] In Modification Example 6, first, the gas volume-specific carbon consumption reduction percentage correlation is obtained in advance similar to Modification Example 4. Moreover, a gas volume-top gas temperature change amount correlation, which is the correlation between the gas volume and the change amount of the top gas temperature with respect to the base operation, is obtained.

[0076] For example, the change amount of the top gas temperature for each of several gas volumes is obtained from the blast furnace operation simulation in which the current blast furnace operation including the blowing temperature of the high-concentration hydrogen-containing gas is reflected. The specific method may be the same as that of the examples described below.

[0077] Next, the values obtained by the above method are plotted on a plane where the horizontal axis is the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas in units of Nm^3/t and the vertical axis in the unit kPa is Δ top gas temperature that is the change amount of the top gas temperature in units of °C. Next, the approximation curve from these plots may be obtained by, for example, the least squares method, and the approximation curve, more specifically, a relational expression showing the approximation curve, may be used as the above-described gas volume-top gas temperature change amount correlation. The gas volume-top gas temperature change amount correlation is preferably obtained for each flame temperature Tf.

[0078] Next, the gas volume in which the reduction percentage Input ΔC of the specific carbon consumption is larger than that of the current operation, that is, the carbon consumption amount is reduced and in which the change amount of the top gas temperature is a value within a predetermined range is determined on the basis of the gas volume-specific carbon consumption reduction percentage correlation and the gas volume-top gas temperature change amount correlation. Here, the predetermined range is, for example, about -20 to + 20°C, but is not limited thereto. Next, the high-concentration hydrogen-containing gas is blown from the tuyere at the determined gas volume. Accordingly, the reduction percentage Input ΔC of the specific carbon consumption can be more reliably increased while the change amount of the top gas temperature is set to a value within a predetermined range.

[0079] Here, in the above Modification Examples 4 to 6, the parameter paired with the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is not necessarily limited to the reduction percentage Input ΔC of the specific carbon consumption. That is, the parameter paired with the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas may be any parameter related to the carbon consumption amount, that is, any carbon consumption parameter. This is because if the carbon consumption amount is reduced, the CO_2 emissions can be reduced. Examples of such a carbon consumption parameter include the specific carbon consumption, the reducing material ratio, the reduction percentage of the reducing material ratio, and the like in addition to the reduction percentage Input ΔC of the specific carbon consumption. The reduction percentage of the reducing material ratio is the reduction percentage of the reducing material ratio with respect to the base operation, and the calculation method is the same as the calculation method of the reduction percentage Input ΔC of the specific carbon consumption.

[0080] Moreover, Modification Example 5 and Modification Example 6 may be combined with each other. Accordingly, the reduction percentage Input ΔC of the specific carbon consumption can be more reliably increased while the change amount of the pressure loss and the change amount of the top gas temperature are set to values within a predetermined ranges.

[Examples]

[0081] Next, examples of the present embodiment will be described. In the present embodiment, it was confirmed by performing the blast furnace operation simulation that the reduction percentage Input ΔC of the specific carbon consumption increases due to the blast furnace operation method according to the present embodiment, that is, the CO2 emissions are reduced.

<1. Example 1: Verification in a case where blowing temperature of high-concentration hydrogen-containing gas is room temperature to 600°C>

[0082] As described above, the correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and the reduction percentage Input ΔC of the specific carbon consumption shows a different behavior with the blowing temperature of 600°C as a boundary. Thus, in Example 1, verification was performed in a case where the blowing temperature of the high-concentration hydrogen-containing gas was 600°C or lower.

<1-1. Model and calculation conditions used for simulation>

[0083] As the blast furnace operation simulation, a so-called "Blast Furnace Mathematical Model" Kouji TAKATANI, Takanobu INADA, Yutaka UJISAWA, "Three-dimensional Dynamic Simulator for Blast Furnace", ISIJ International, Vol. 39 (1999), No. 1, pp. 15 to 22 was used. In this blast furnace mathematical model, an internal region of the blast furnace is divided in a height direction, a radial direction, and a circumferential direction to define a plurality of meshes (small regions), and the behavior of each of the meshes is simulated.

[0084] In the blast furnace mathematical model, the gas volume of the high-concentration hydrogen-containing gas is set as the amount of the high-concentration hydrogen-containing gas blown from the tuyere. Of these, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is set as the amount obtained by multiplying the gas volume of the high-concentration hydrogen-containing gas by the ratio of the hydrogen gas in units of mol%. The blowing temperature of the high-concentration hydrogen-containing gas is set as the temperature of the high-concentration hydrogen-containing gas when the high-concentration hydrogen-containing gas is blown from the tuyere. The flame temperature Tf is calculated as a result of considering the combustion heat of various gases, the sensible heat of blast, the temperature of the coke flowing into the tuyere tip (the outlet of the tuyere), various reaction heats, and the like. The pressure loss is calculated using the Ergun equation as the pressure loss of a packed bed inside the furnace. The top gas temperature is calculated as the gas temperature in the outermost layer (uppermost layer) of the charges inside the furnace.

[0085] The calculation conditions are shown in Table 1. The coke ratio in Table 1 is the amount of coke used per ton of molten iron. Additionally, Table 2 shows the specifications of the base operation in which high-concentration hydrogen-containing gas is not blown in. As shown in Tables 1 and 2, in the present example, the flame temperature Tf was set to any of 2000°C, 2100°C, or 2200°C. Additionally, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas was set to 0 to 600 Nm^3/t. Additionally, the blast volume, the oxygen enrichment ratio, and the gas volume of PC (pulverized coal) were adjusted such that the tapped iron ratio and the molten iron temperature were constant in all operations.

[Table 1]

Calculation conditions		
Tapped iron ratio	$t/d/m^3$	About 2.7 (Constant)
Molten iron temperature	°C	1535 to 1540
Blast volume	Nm^3/min	Adjusted
Oxygen enrichment ratio	%	Adjusted
Pre-tuyere temperature	°C	2000, 2100, 2200
Gas volume of hydrogen gas into high-concentration hydrogen-containing gas	Nm^3/t	0 to 600
Blowing temperature of high-concentrati on h ydrogen-contai ni ng gas	°C	25 to 600
Coke ratio	kg/t	300 (Constant)
Gas volume of pulverized coal	tons/h	Adjusted

[Table 2]

Base operation specifications at pre-tuyere temperatures of 2000°C, 2100°C, and 2200°C				
		2000°C	2100°C	2200°C
Tapped ion ratio	$t/d/m^3$	2.74	2.74	2.74
Blast volume	Nm^3/min	9440	7800	6300
Oxygen enrichment ratio	%	1.2	4.8	9.2
Gas volume of hydrogen gas into high-concentration hydrogen-containing gas	Nm^3/t	0	0	0
Coke ratio	kg/t	306.6	306.6	306.6
Pulverized coal ratio	kg/t	201.4	200.1	200.2
Molten iron temperature	°C	1537	1536	1536

[0086] In addition, the iron-bearing materials were all sintered ores. Additionally, the composition of the sintered ores was T-Fe: 58.5%, FeO: 7.5%, C/S: 1.9, and Al_2O_3: 1.7%. Additionally, regarding coke, a case where C: 87.2% and ash: 12.6% was used was assumed. In addition, all of the above "%" represent "mass%".

<1-2. Example 1-1: Case where blowing temperature of high-concentration hydrogen-containing gas is room temperature to 600°C and high-concentration hydrogen-containing gas is pure hydrogen gas>

[0087] In Example 1-1, the correlation between the gas volume of the pure hydrogen gas and the reduction percentage Input ΔC of the specific carbon consumption was calculated using the high-concentration hydrogen-containing gas as the pure hydrogen gas, under the condition that the blowing temperature of the high-concentration hydrogen-containing gas was 600°C or lower. The results are shown in FIGS. 2 to 5.

[0088] As shown in FIGS. 2 to 5, it was found that, in a range where the blowing temperature is at room temperature or higher and 600°C or lower, the reduction percentage Input ΔC of the specific carbon consumption does not simply increase with an increase in the gas volume but reaches saturation and starts to decrease when the gas volume of air increases to some extent. Then, it was found that the gas volume when the reduction percentage Input ΔC of the specific carbon consumption reaches saturation and starts to decrease is slightly different depending on the blowing temperature. That is, it was found that an appropriate range of the gas volume is present for each blowing temperature. The appropriate range was 200 to 500 Nm^3/t in a case where the blowing temperature was room temperature to 300°C and was 145 Nm^3/t or more when the blowing temperature was higher than 300°C and 600°C or lower. Additionally, as shown in FIGS. 4 and 5, it was found that the reduction percentage Input ΔC of the specific carbon consumption does not simply increase with an increase in the gas volume but reaches saturation at a gas volume of about 600 Nm^3/t when the blowing temperature is 600°C and starts to decrease with an increase in the gas volume at a gas volume peak of about 300 Nm^3/t when the blowing temperature is 350°C. Also, in a case where the blowing temperature is higher than 300°C and 600°C or lower and the gas volume is within an appropriate range of 145 Nm^3/t or more, it is possible to set the reduction percentage Input ΔC of the specific carbon consumption to 7% or more. Moreover, as shown in FIGS. 2 to 5, it was also found that the reduction percentage Input ΔC of the specific carbon consumption with respect to the same gas volume varies depending on the flame temperature Tf and is the largest when the flame temperature Tf is 2000°C. The reason why such a phenomenon is obtained is as described above.

[0089] Therefore, by blowing the high-concentration hydrogen-containing gas in the blast furnace according to the blast furnace operation method according to the present embodiment, the reduction percentage Input ΔC of the specific carbon consumption can be increased, and the CO_2 emissions can be significantly reduced.

<1-3. Example 1-2>

[0090] In Example 1-2, it was confirmed that even if the high-concentration hydrogen-containing gas contains a gas component other than the hydrogen gas, the same operation as in the case of the pure hydrogen gas is possible. Specifically, 80 mol% H_2-20 mol% N_2 gas composed of 80 mol% hydrogen gas and 20 mol% nitrogen gas was assumed as the high-concentration hydrogen-containing gas. Then, the blast furnace operation simulation was performed in the same manner as in Example 1 with the blowing temperature set to 25°C and the flame temperature Tf set to 2100°C. The results are shown in FIG. 11. FIG. 11 shows a comparison between the calculation result of the pure hydrogen gas (100 mol% H2 gas) and the calculation result of 80 mol% H_2-20 mol% N_2 gas. In addition, the horizontal axis in FIG. 11 represents a value obtained by converting the flow rate of a mixed gas in the pure hydrogen gas, that is, a value obtained by multiplying the flow rate of 80 mol% H_2-20 mol% N_2 gas by 80 mol%. As is clear from FIG. 11, it was found that, for 80 mol% H_2-20 mol% N_2 gas, the appropriate range of the gas volume converted into the pure hydrogen gas is the same as that of the pure hydrogen gas and only the effect cost decreases slightly. Therefore, it was found that even when the high-concentration hydrogen-containing gas contains a gas component other than the hydrogen gas, the same operation as in the case of the pure hydrogen gas is possible. Additionally, it was also found that the reduction percentage Input ΔC of the specific carbon consumption can be increased, although the effect is slightly reduced.

<1-4. Example 1-3>

[0091] In Example 1-3, the pure hydrogen gas at room temperature was used as the high-concentration hydrogen-containing gas, and the change amount of the pressure loss with respect to each of several gas volumes (the change amount of the pressure loss with respect to the base operation) was obtained. FIG. 12 shows the results. As is clear from FIG. 12, it was found that there is a certain correlation between the gas volume of the pure hydrogen gas and the change amount of the pressure loss. For example, it was found that there is a possibility of the pressure loss being large with respect to the base operation in a case where the flame temperature Tf is low. However, the pressure loss decreases when the gas volume of the pure hydrogen gas increases. More specifically, in a case where the flame temperature Tf is 2000°C and the gas volume is 100 to 150 Nm^3/t, the pressure loss increases by about 10 to 20 kPa as compared to the base operation. This is a value outside the predetermined range described above. However, when the gas volume increases to 200 Nm^3/t or more, the pressure loss is almost the same as or less than the value of the base operation. The reason why such a phenomenon occurs is as described above. Therefore, it was found that it is possible to suppress the increase in the pressure loss and increase the unit reduction percentage Input ΔC of the specific carbon consumption while performing a stable operation, by obtaining the gas volume-pressure drop change correlation, which is the correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and the change amount of the pressure loss with respect to the base operation when the blowing temperature is a predetermined value, in advance for each flame temperature Tf and by determining the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas at which the carbon consumption amount is reduced compared to that of the current operation, and the change amount of the pressure loss is a value within a predetermined range on the basis of the gas volume-carbon consumption parameter correlation and the gas volume-pressure drop change correlation.

[0092] Then, it was found that it is possible to suppress the increase in the pressure loss and increase the reduction percentage Input ΔC of the specific carbon consumption while performing a stable operation as shown in FIG. 12, under the conditions that the pure hydrogen gas at room temperature is used as the high-concentration hydrogen-containing gas and the gas volume is 200 Nm^3/t or more and 500 Nm^3/t or less. It was found that when the gas volume increases to 200 Nm^3/t in the case of the pure hydrogen gas at room temperature or higher and 300°C or lower, the pressure loss is almost the same as or equal to or less than the value of the base operation. Similarly, it was found that it is possible to suppress the increase in the pressure loss and increase the reduction percentage Input ΔC of the specific carbon consumption while performing a stable operation in a case where the gas volume of the pure hydrogen at higher than 300°C and 600°C or lower is 145 Nm^3/t or more, even in a case where the gas volume of the pure hydrogen at higher than 600°C and 900°C or lower is 125 Nm^3/t or more, even in a case where the gas volume of the pure hydrogen at higher than 900°C and 1200°C or lower is 110 Nm^3/t or more, and even in a case where the gas volume of the pure hydrogen at higher than 1200°C is 100 Nm^3/t or more.

[0093] Therefore, it was found that it is possible to increase the reduction percentage Input ΔC of the specific carbon consumption while setting the change amount of the pressure loss to a value within a predetermined range by blowing the high-concentration hydrogen-containing gas in the blast furnace according to the blast furnace operation method according to the present embodiment.

<1-5. Example 1-4>

[0094] In Example 1-4, the pure hydrogen gas at room temperature was used as the high-concentration hydrogen-containing gas, and the change amount of the top gas temperature with respect to each of several gas volumes (the change amount of the top gas temperature with respect to the base operation) was obtained. FIG. 13 shows the results. As is clear from FIG. 13, it was found that there is a certain correlation between the gas volume of the pure hydrogen gas and the change amount of the top gas temperature. For example, when the flame temperature Tf increases, the top gas temperature decreases as compared to the base operation. Specifically, in a case where the flame temperature Tf is 2100°C and the gas volume is 250 to 300 Nm^3/t, the change amount of the top gas temperature is a value outside the above-described predetermined range. However, if the gas volume decreases to 200 Nm^3/t, the change amount of the top gas temperature becomes a value within a predetermined range. The reason why such a phenomenon occurs is as described above. Therefore, in a case where the efficiency of operation or the like is emphasized, the gas volume may be adjusted in consideration of the correlation between the gas volume of the pure hydrogen gas and the change amount of the top gas temperature. Therefore, it was found that it is possible to suppress the decrease in the efficiency of the operation by obtaining the gas volume-top gas temperature change amount correlation, which is the correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and the change amount of the top gas temperature with respect to the base operation when the blowing temperature is a predetermined value, in advance for each flame temperature Tf and by determining the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas at which the carbon consumption amount is reduced compared to that of the current operation, and the change amount of the top gas temperature is a value within a predetermined range on the basis of the gas volume-carbon consumption parameter correlation and the gas volume-top gas temperature change amount correlation.

<2. Example 2: Verification in case where blowing temperature of high-concentration hydrogen-containing gas is higher than 600°C>

[0095] In Example 2, a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C was verified.

<2-1. Model and calculation conditions used for simulation>

[0096] In the blast furnace operation simulation, the same "blast furnace mathematical model" as in Example 1 was used. Calculation conditions are shown in Table 3. As shown in Table 3, the calculation conditions were almost the same as those in Example 1, but the coke ratio was different from that in Example 1. That is, in Example 2, the coke ratio was constant at 300 kg/t in a case where the pulverized coal gas volume was larger than 0 tons/h, and the coke ratio fluctuated in a case where the pulverized coal gas volume was 0 tons/h (that is, in a case where the pulverized coal ratio was 0). That is, in a case where the gas volume of the pulverized coal was 0 tons/h, the furnace temperature was adjusted according to the coke ratio.

[0097] As described above, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is increased and the gas volume is increased, the gas volume of the pulverized coal may be 0 tons/h. In this case, by reducing the coke ratio, it is possible to further reduce the specific carbon consumption. Additionally, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas was set to 0 to 1000 Nm^3/t. Additionally, the blowing temperature of the high-concentration hydrogen-containing gas was set to higher than 600°C and 1400°C or less. In addition, the specifications of the base operation in which the high-concentration hydrogen-containing gas was not blown were the same as in Example 1. Other conditions were the same as those of Example 1. For example, the blast volume, the oxygen enrichment ratio, and the gas volume of PC (pulverized coal) were adjusted such that the tapped iron ratio and the molten iron temperature were constant in all operations. The iron-bearing materials were sintered ore used in Example 1.

[Table 3]

Calculation conditions		
Tapped iron ratio	$t/d/m^3$	About 2.7 (constant)
Molten iron temperature	°C	1535 to 1540
Blast volume	Nm^3/min	Adjusted
Oxygen enrichment ratio	%	Adjusted
Pre-tuyere temperature	°C	2000, 2100, 2200
Gas volume of hydrogen gas into high-concentration hydrogen-containing gas	Nm^3/t	0 to 1000
Blowing temperature of high-concentration hydrogen-containing gas	°C	Higher than 600 and 1400 or lower
Coke ratio	kg/t	300 (constant in case where gas volume of pulverized coal is more than 0 tons/h)
Gas volume of pulverized coal	tons/h	Adjusted

<2-2. Example 2-1: Case where blowing temperature of high-concentration hydrogen-containing gas is higher than 600°C and high-concentration hydrogen-containing gas is pure hydrogen gas>

[0098] In Example 2-1, the correlation between the gas volume of the pure hydrogen gas and the reduction percentage Input ΔC of the specific carbon consumption was calculated using the high-concentration hydrogen-containing gas as the pure hydrogen gas. The results are shown in FIGS. 6 to 10.

[0099] As shown in FIGS. 6 to 10, it was found that the reduction percentage Input Δ C of the specific carbon consumption increases when the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is increased from 0 Nm^3/t in the base operation. Moreover, as the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas increases, the increase rate of the reduction percentage Input ΔC of the specific carbon consumption (increase amount of the reduction percentage Input ΔC of the specific carbon consumption to the unit increase amount of the gas volume) decreases. However, the reduction percentage Input ΔC of the specific carbon consumption did not start to decrease. This behavior was clearly different from the case where the blowing temperature of the high-concentration hydrogen-containing gas was 600°C or lower.

[0100] In addition, a range where the reduction percentage Input ΔC of the specific carbon consumption was 7% or more was different depending on the blowing temperature of the high-concentration hydrogen-containing gas. Specifically, in a case where the blowing temperature was higher than 600°C and 900°C or lower and in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas was within a range of 125 Nm^3/t or more, the reduction percentage Input ΔC of the specific carbon consumption was 7% or more. Additionally, in a case where the blowing temperature was higher than 900°C and 1200°C or lower and in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas was within a range of 110 Nm^3/t or more, the reduction percentage Input ΔC of the specific carbon consumption was 7% or more. In a case where the blowing temperature was higher than 1200°C and in a case where the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas was within a range of 100 Nm^3/t or more, the reduction percentage Input ΔC of the specific carbon consumption was 7% or more.

<2-3. Other tests>

[0101] The same test as in Examples 1-3 and 1-4 was performed with the blowing temperature of the pure hydrogen gas set to 900°C. As a result, even in a case where the blowing temperature of the pure hydrogen gas was 900°C, it was confirmed that there is a certain correlation between the gas volume of the pure hydrogen gas and the change amount of the pressure loss or the change amount of the top gas temperature.

[0102] Therefore, it is possible to increase the reduction percentage Input ΔC of the specific carbon consumption while setting the change amount of the top gas temperature to a value within a predetermined range by blowing the high-concentration hydrogen-containing gas in the blast furnace according to the blast furnace operation method according to the present embodiment.

[0103] Although the preferred embodiment of the present invention has been described above in detail with reference to the accompanying drawings, the present invention is not limited to such an example. It is apparent that those having ordinary knowledge in the technical field to which the present invention belongs can conceive various changes or alterations within the scope of the technical ideas described in the claims, and it is naturally understood that these also belong to the technical scope of the present invention.

Claims

1. A blast furnace operation method comprising blowing a high-concentration hydrogen-containing gas containing 80 mol% or more of hydrogen gas from a tuyere under:

    a condition in which a blowing temperature of the high-concentration hydrogen-containing gas is room temperature or higher and 300°C or lower and a gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 200 Nm^3/t or more and 500 Nm^3/t or less;
    a condition in which the blowing temperature of the high-concentration hydrogen-containing gas is higher than 300°C and 600°C or lower and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 145 Nm^3/t or more;
    a condition in which the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C and 900°C or lower and the gas volume of the high-concentration hydrogen-containing gas is 125 Nm^3/t or more;
    a condition in which the blowing temperature of the high-concentration hydrogen-containing gas is higher than 900°C and 1200°C or lower and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 110 Nm^3/t or more; or
    a condition in which the blowing temperature of the high-concentration hydrogen-containing gas is higher than 1200°C and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 100 Nm^3/t or more.

2. The blast furnace operation method according to claim 1,
   wherein the blowing temperature is higher than room temperature and 300°C or lower and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 200 Nm^3/t or more and 300 Nm^3/t or less.

3. The blast furnace operation method according to claim 1,
   wherein the blowing temperature of the high-concentration hydrogen-containing gas is higher than 300°C and 600°C or lower and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 145 Nm^3/t or more and 600 Nm^3/t or less.

4. The blast furnace operation method according to any one of claims 1 to 3, wherein a flame temperature is 2050°C or lower.

5. The blast furnace operation method according to any one of claims 1 to 3, wherein a flame temperature is higher than 2050°C and 2150°C or lower.

6. The blast furnace operation method according to any one of claims 1 to 3, wherein a flame temperature is higher than 2150°C and 2250°C or lower.

7. The blast furnace operation method according to claim 1,
   wherein the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C and 1400°C or lower.

8. The blast furnace operation method according to claim 1 or 7,
   wherein, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than

600°C, the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 1000 Nm^3/t or less.

9. The blast furnace operation method according to any one of claims 1, 7, and 8,
wherein, in a case where the blowing temperature of the high-concentration hydrogen-containing gas is higher than 600°C and the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas is 400 Nm^3/t or more, a flame temperature is set to 2050°C or lower.

10. A blast furnace operation method comprising:

obtaining a gas volume-carbon consumption parameter correlation, which is a correlation between a gas volume of hydrogen gas in a high-concentration hydrogen-containing gas and a carbon consumption parameter related to a carbon consumption amount when a blowing temperature of the high-concentration hydrogen-containing gas containing 80 mol% or more of the hydrogen gas is a predetermined value, in advance for each flame temperature;
determining the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas at which the carbon consumption amount is reduced compared to that of a current operation, on the basis of the gas volume-carbon consumption parameter correlation; and
blowing the high-concentration hydrogen-containing gas from the tuyere at the determined gas volume.

11. The blast furnace operation method according to claim 10,
wherein the gas volume-carbon consumption parameter correlation is obtained for each blowing temperature.

12. The blast furnace operation method according to claim 10 or 11,

wherein a gas volume-pressure drop change correlation, which is a correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and a change amount of a pressure loss with respect to a base operation when the blowing temperature is a predetermined value, is obtained in advance for each flame temperature, and
the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas at which the carbon consumption amount is reduced compared to that of the current operation and the change amount of the pressure loss is a value within a predetermined range is determined on the basis of the gas volume-carbon consumption parameter correlation and the gas volume-pressure drop change correlation.

13. The blast furnace operation method according to any one of claims 10 to 12,

wherein a gas volume-top gas temperature change amount correlation, which is a correlation between the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas and a change amount of a top gas temperature with respect to a base operation when the blowing temperature is a predetermined value, is obtained in advance for each flame temperature, and
the gas volume of the hydrogen gas in the high-concentration hydrogen-containing gas at which the carbon consumption amount is reduced compared to that of the current operation and the change amount of the top gas temperature is a value within a predetermined range is determined on the basis of the gas volume-carbon consumption parameter correlation and the gas volume-top gas temperature change amount correlation.

FIG. 1

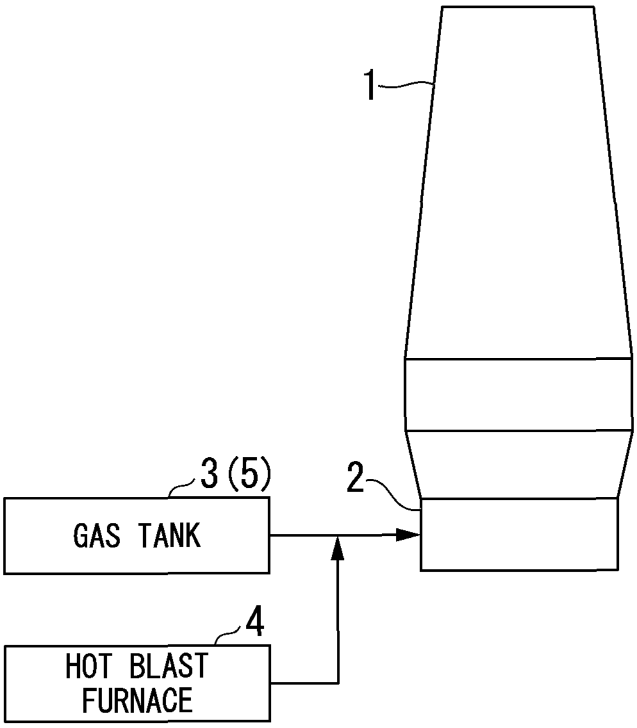

1
2
3 (5)
GAS TANK
4
HOT BLAST FURNACE

FIG. 2

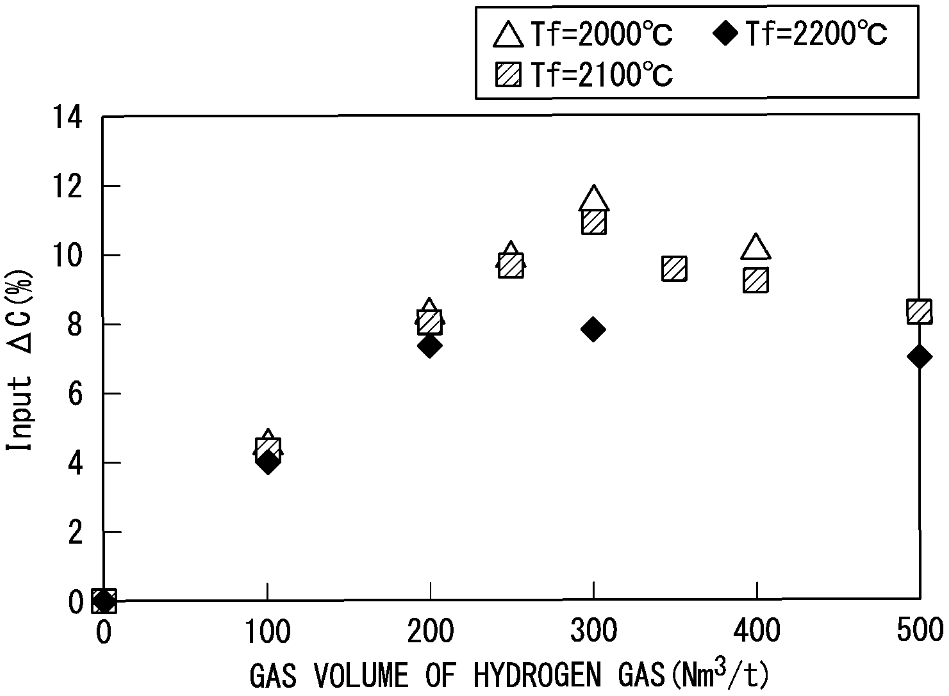

△ Tf=2000℃
◆ Tf=2200℃
▨ Tf=2100℃
Input ΔC (%)
0
2
4
6
8
10
12
14
0
100
200
300
400
500
GAS VOLUME OF HYDROGEN GAS (Nm³/t)

FIG. 3

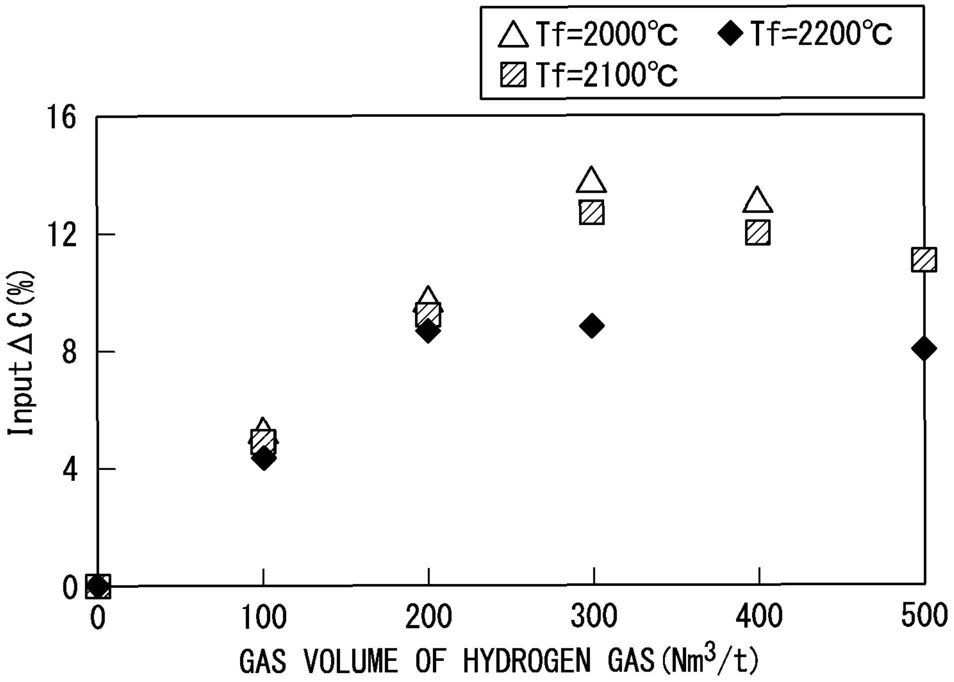

△ Tf=2000℃
◆ Tf=2200℃
▨ Tf=2100℃
16
12
8
4
0
Input ΔC (%)
0
100
200
300
400
500
GAS VOLUME OF HYDROGEN GAS (Nm3/t)

FIG. 4

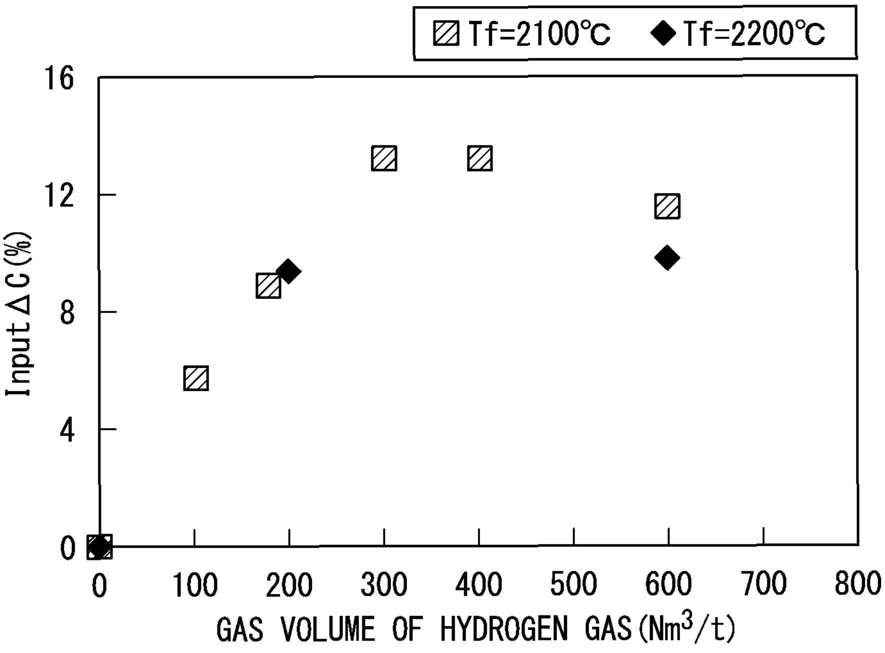

▨ Tf=2100℃
◆ Tf=2200℃
16
12
8
4
0
Input ΔC (%)
0
100
200
300
400
500
600
700
800
GAS VOLUME OF HYDROGEN GAS (Nm3/t)

FIG. 5

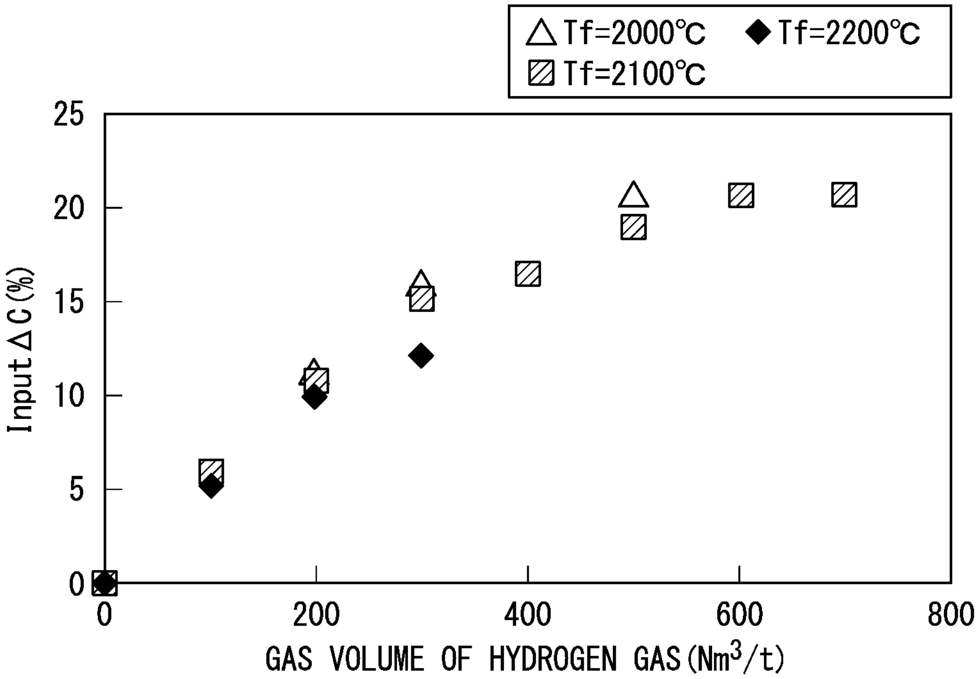

△Tf=2000℃
◆Tf=2200℃
▨Tf=2100℃
Input ΔC(%)
25
20
15
10
5
0
0
200
400
600
800
GAS VOLUME OF HYDROGEN GAS(Nm^3/t)

FIG. 6

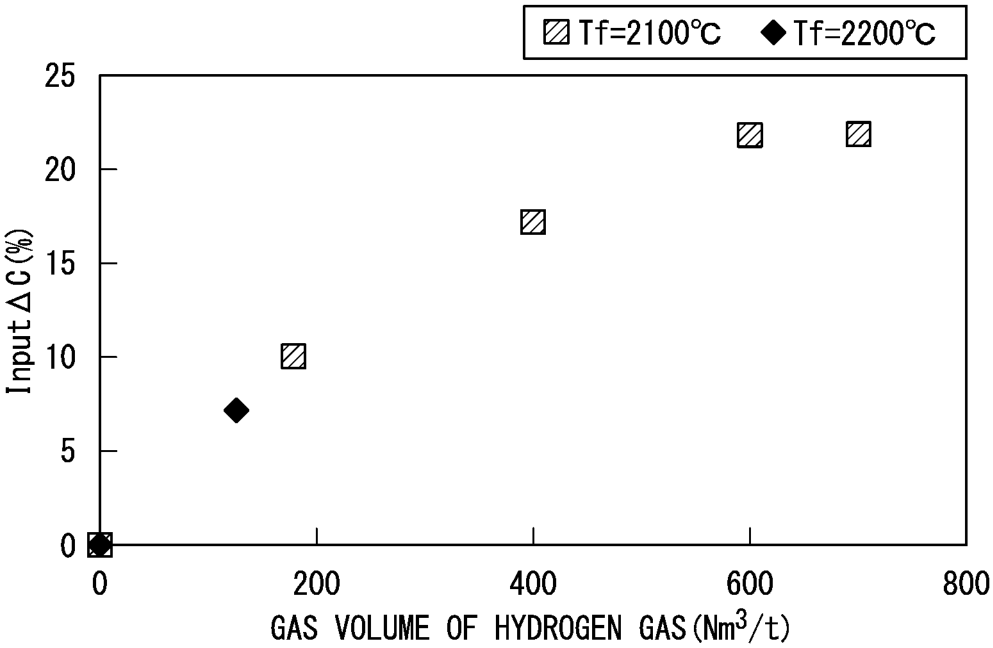

▨Tf=2100℃
◆Tf=2200℃
Input ΔC(%)
25
20
15
10
5
0
0
200
400
600
800
GAS VOLUME OF HYDROGEN GAS(Nm^3/t)

FIG. 7

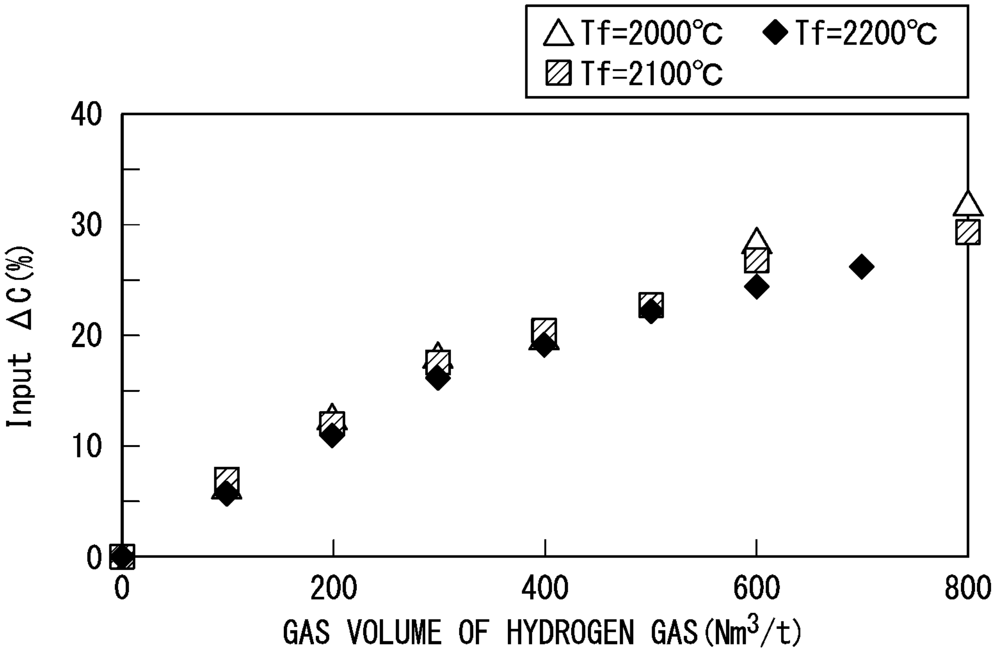

△Tf=2000°C
◆Tf=2200°C
▨Tf=2100°C
Input ΔC(%)
0
10
20
30
40
0
200
400
600
800
GAS VOLUME OF HYDROGEN GAS(Nm³/t)

FIG. 8

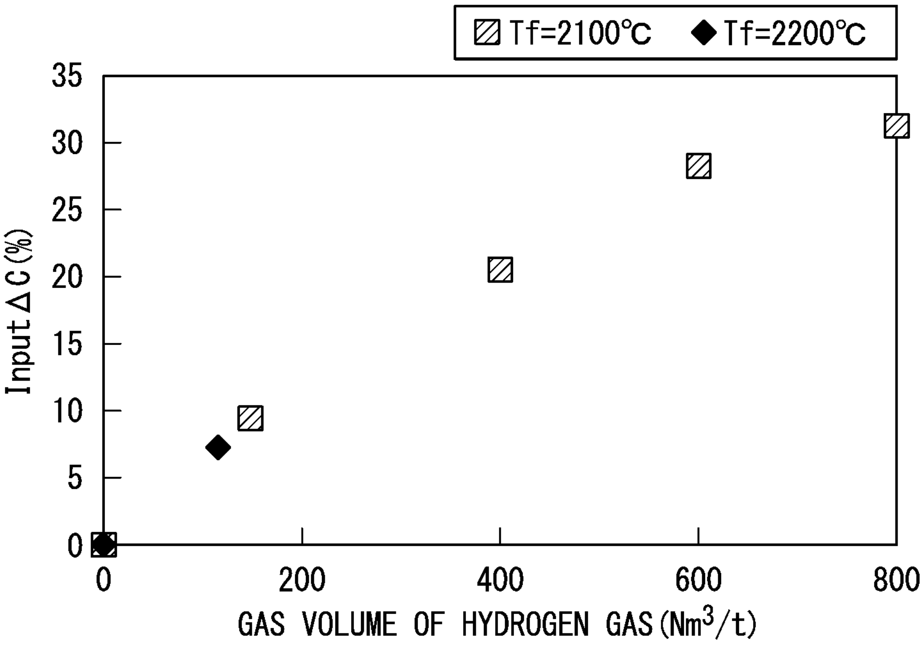

▨Tf=2100°C
◆Tf=2200°C
Input ΔC(%)
0
5
10
15
20
25
30
35
0
200
400
600
800
GAS VOLUME OF HYDROGEN GAS(Nm³/t)

FIG. 9

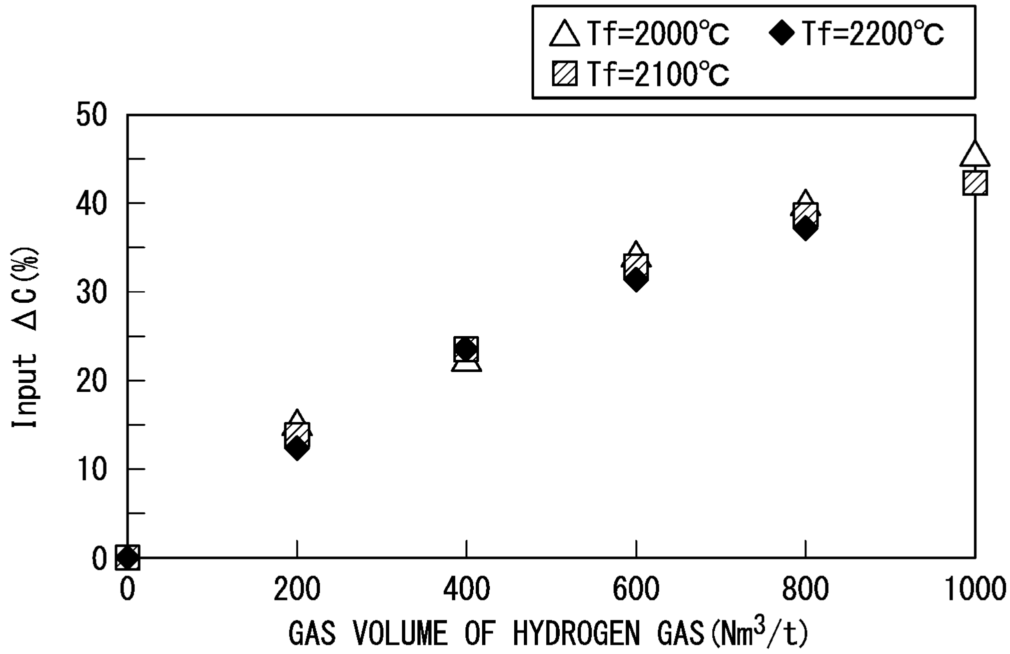

△Tf=2000℃
◆Tf=2200℃
▨Tf=2100℃
Input ΔC(%)
0
10
20
30
40
50
0
200
400
600
800
1000
GAS VOLUME OF HYDROGEN GAS(Nm3/t)

FIG. 10

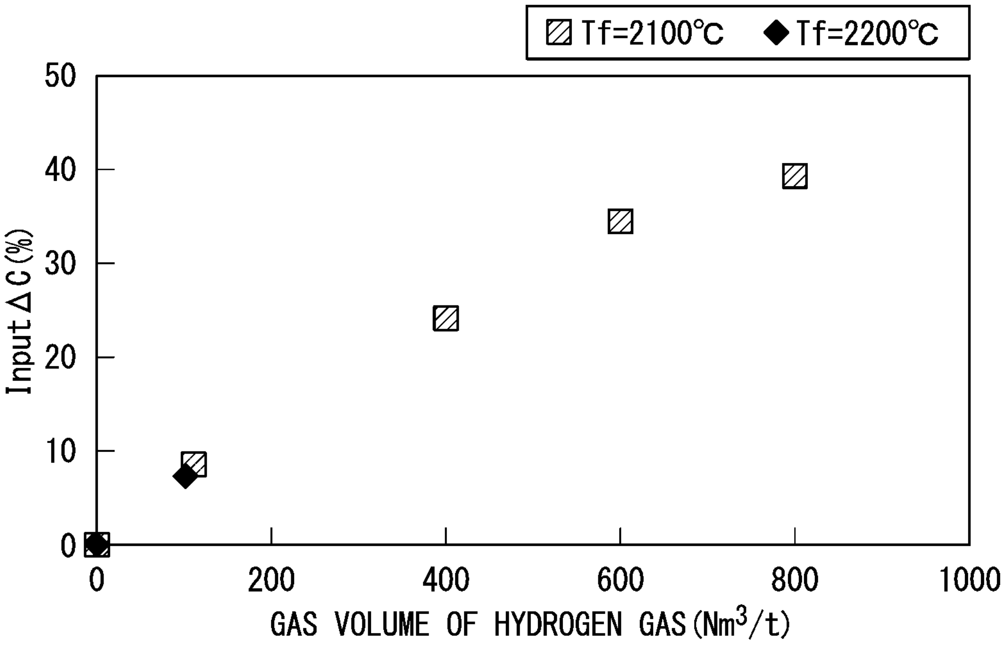

▨Tf=2100℃
◆Tf=2200℃
InputΔC(%)
0
10
20
30
40
50
0
200
400
600
800
1000
GAS VOLUME OF HYDROGEN GAS(Nm3/t)

FIG. 11

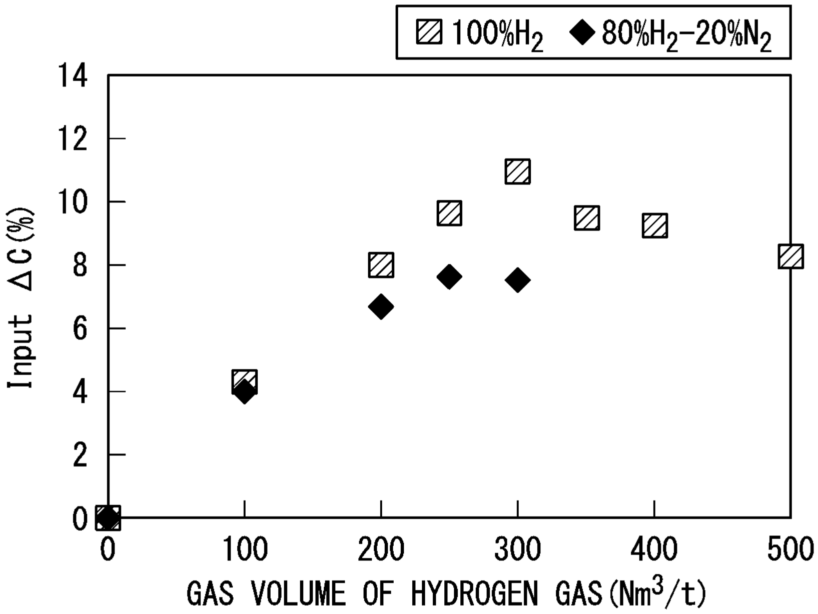

▨ 100%H_2 ◆ 80%H_2-20%N_2
Input ΔC(%)
14
12
10
8
6
4
2
0
0
100
200
300
400
500
GAS VOLUME OF HYDROGEN GAS (Nm^3/t)

FIG. 12

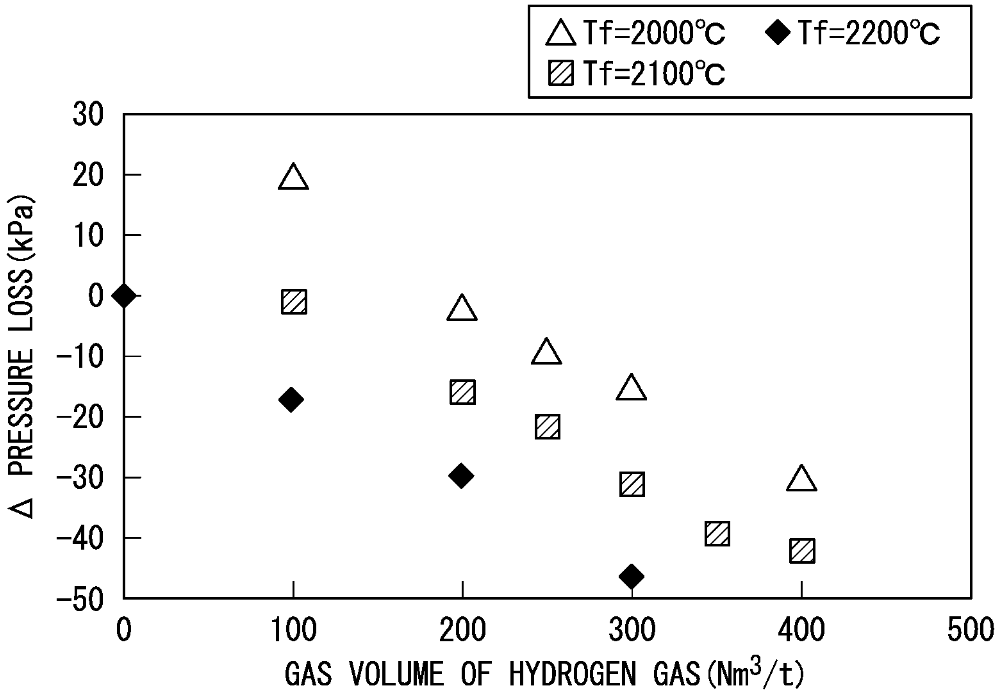

△ Tf=2000℃ ◆ Tf=2200℃
▨ Tf=2100℃
Δ PRESSURE LOSS (kPa)
30
20
10
0
-10
-20
-30
-40
-50
0
100
200
300
400
500
GAS VOLUME OF HYDROGEN GAS (Nm^3/t)

FIG. 13

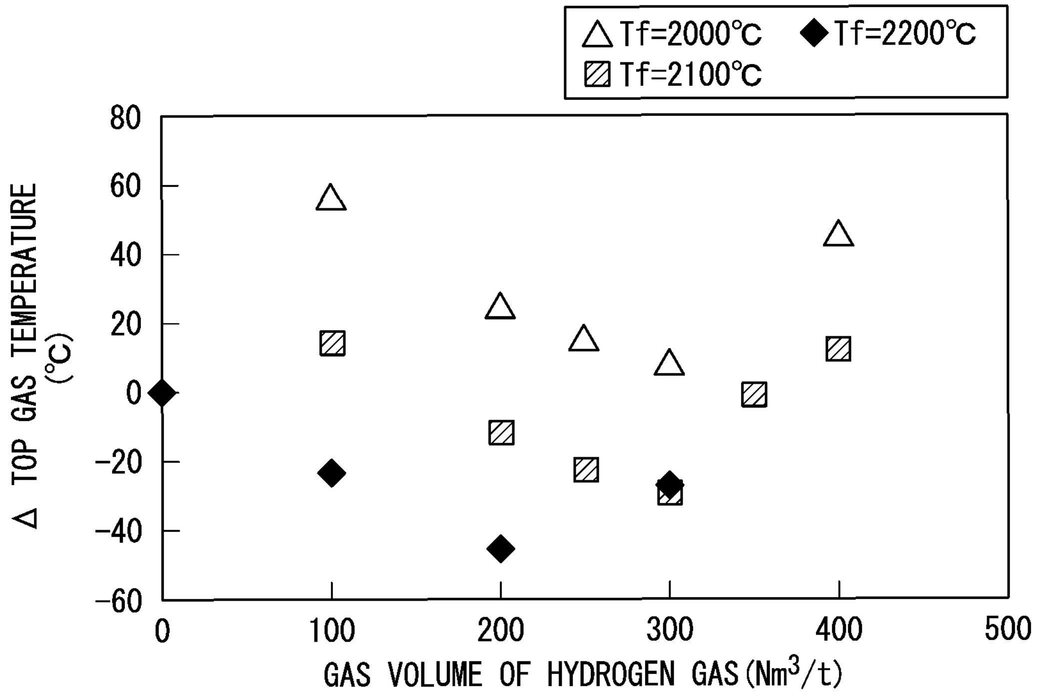

△Tf=2000℃
◆Tf=2200℃
▨Tf=2100℃
Δ TOP GAS TEMPERATURE (℃)
80
60
40
20
0
-20
-40
-60
0
100
200
300
400
500
GAS VOLUME OF HYDROGEN GAS (Nm³/t)

FIG. 14

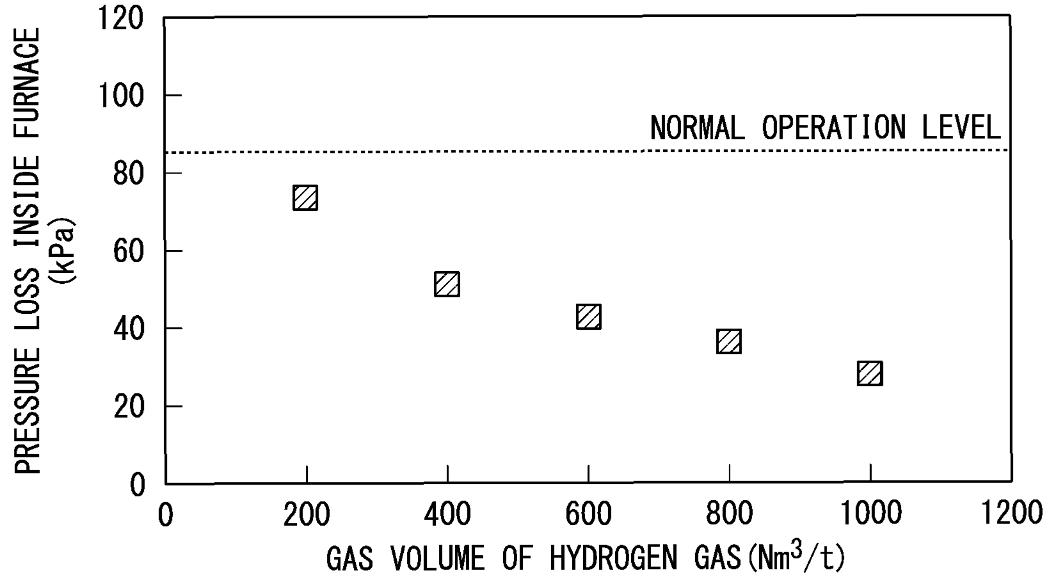

PRESSURE LOSS INSIDE FURNACE (kPa)
120
100
80
60
40
20
0
NORMAL OPERATION LEVEL
0
200
400
600
800
1000
1200
GAS VOLUME OF HYDROGEN GAS (Nm³/t)

FIG. 15

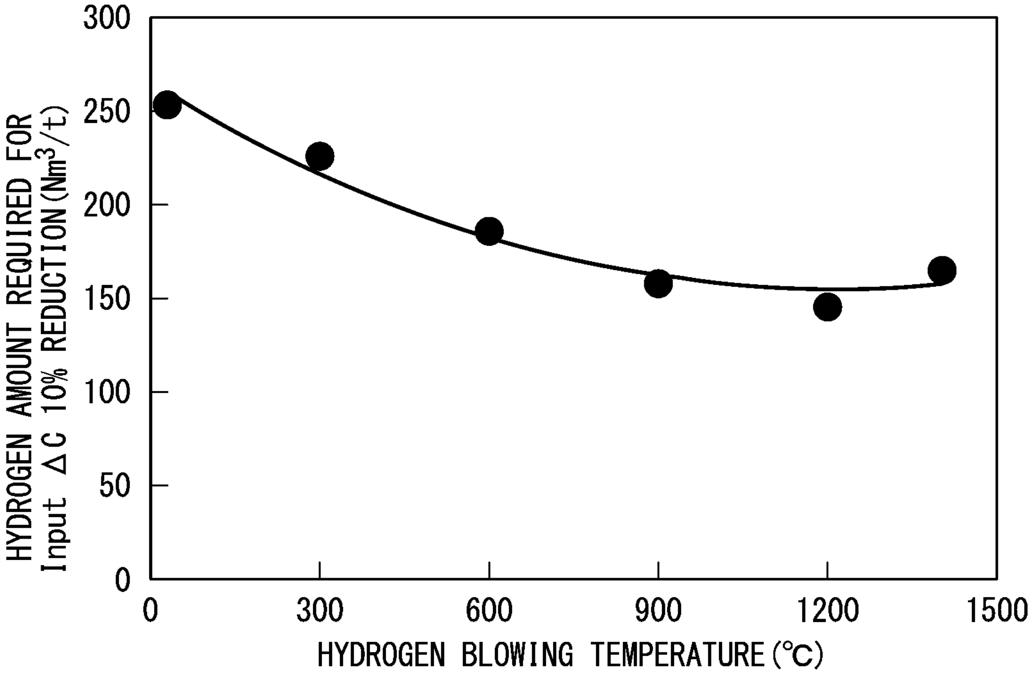
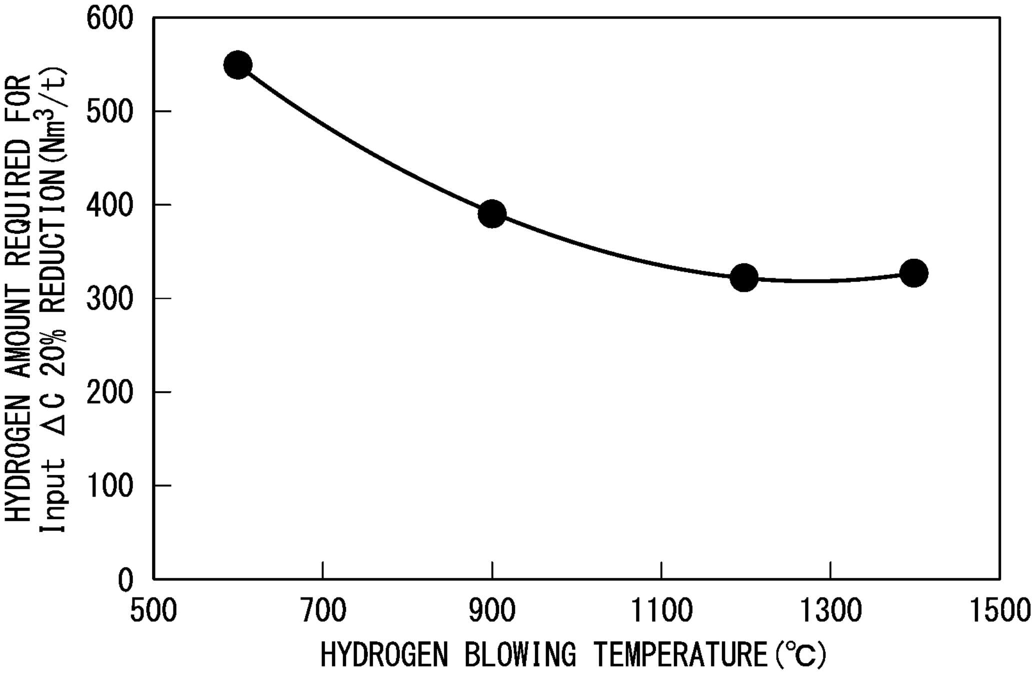

300
250
200
150
100
50
0
HYDROGEN AMOUNT REQUIRED FOR
Input ΔC 10% REDUCTION(Nm³/t)
0
300
600
900
1200
1500
HYDROGEN BLOWING TEMPERATURE(℃)

FIG. 16


600
500
400
300
200
100
0
HYDROGEN AMOUNT REQUIRED FOR
Input ΔC 20% REDUCTION(Nm³/t)
500
700
900
1100
1300
1500
HYDROGEN BLOWING TEMPERATURE(℃)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2020/044217

A. CLASSIFICATION OF SUBJECT MATTER
Int.Cl. C21B5/00(2006.01)i
FI: C21B5/00321

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)
Int.Cl. C21B3/00-5/06, 11/00-15/04

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	1971-2021
Registered utility model specifications of Japan	1996-2021
Published registered utility model applications of Japan	1994-2021

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	WO 2017/134829 A1 (NIPPON STEEL & SUMITOMO METAL CORPORATION; JFE STEEL CORPORATION; KOBE STEEL, LTD.; NISSHIN STEEL CO., LTD.; NIPPON STEEL & SUMIKIN ENGINEERING CO., LTD.) 10 August 2017 (2017-08-10), entire text, all drawings	1-13
A	JP 58-87210 A (KAWASAKI STEEL CORP.) 25 May 1983 (1983-05-25), entire text, all drawings	1-13
A	JP 6-57315 A (NIPPON STEEL CORPORATION) 01 March 1994 (1994-03-01), entire text, all drawings	1-13

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

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

Date of the actual completion of the international search
19 January 2021

Date of mailing of the international search report
02 February 2021

Name and mailing address of the ISA/
Japan Patent Office
3-4-3, Kasumigaseki, Chiyoda-ku,
Tokyo 100-8915, Japan

Authorized officer

Telephone No.

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

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2020/044217

WO 2017/134829 A1	10 August 2017	US 2019/0032160 A1 entire text, all drawings EP 3412780 A1 CN 108699612 A KR 10-2018-0109064 A BR 112018015789 A
JP 58-87210 A	25 May 1983	(Family: none)
JP 6-57315 A	01 March 1994	(Family: none)

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

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- JP 2019216568 A **[0002]**
- JP 2020092467 A **[0002]**
- JP 6019893 B **[0007]**
- JP 5987773 B **[0007]**
- JP 5050706 B **[0007]**
- JP 5770124 B **[0007]**
- JP 5315732 B **[0007]**
- JP 5851828 B **[0007]**

Non-patent literature cited in the description

- **KOUJI TAKATANI ; TAKANOBU INADA ; UTAKA UJISAWA.** Three-dimensional Dynamic Simulator for Blast Furnace. *ISIJ International,* 1999, vol. 39 (1), 15-22 **[0034]**
- **AKITOSHI SHIGEMI.** Ironmaking Handbook. Chijinshokan Co., Ltd, **[0055]**
- **KOUJI TAKATANI ; TAKANOBU INADA ; YUTAKA UJISAWA.** Three-dimensional Dynamic Simulator for Blast Furnace. *ISIJ International,* 1999, vol. 39 (1), 15-22 **[0083]**