Effect of Propane Gas on Hot Metal Desulfurization by CaO Based Flux

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The effect of propane gas blowing on hot metal desulfurization was investigated in laboratory-scale experiments and commercial plant tests. Desulfurization tests were carried out by two methods, flux injection and mechanical stirring.

Flux injection:
In the 4 ton-scale and commercial-scale tests, the flux efficiency for desulfurization increased by 1.2–1.7 times by mixing of propane gas with the nitrogen carrier gas at propane gas ratio of 10–58%. The effect of propane gas mixing on improving desulfurization efficiency is presumed to be caused by a decrease in the local oxygen potential, together with an increase in the interfacial area between hot metal and flux.

Mechanical stirring:
A top-blowing propane gas technique was examined in both 4 ton-scale tests and commercial hot metal desulfurization operation by mechanical stirring with an impeller. The flux efficiency for desulfurization increased by 1.25 times with top-blowing propane gas. The presumed effects of the top-blowing propane gas are enhancement of stirring energy in addition to reduction of the oxygen potential in hot metal and increase in the interfacial area between hot metal and flux. The sulfur partition ratio between slag and hot metal with mechanical stirring was higher than that with flux injection in a torpedo car at the same oxygen potential level with utilizing propane gas.

KEY WORDS: hot metal; desulfurization; CaO; propane gas; torpedo car; mechanical stirring.

1. Introduction

Demand for ultra-low sulfur grade steel in heavy plates and linepipe steel is currently increasing. In order to meet this demand, and achieve higher productivity and lower production costs at the same time, high efficiency hot metal desulfurization is required. From the viewpoints of reducing CO₂ emissions and slag generation, higher efficiency of flux for desulfurization is desired. The hot metal desulfurization process can be broadly categorized into two methods, namely, flux injection in a torpedo car¹ or hot metal transfer ladle,²³ and mechanical stirring by an impeller.³ JFE Steel Corporation (former Kawasaki Steel Corporation) adopted the flux injection method in the torpedo car. However, the initial hot metal temperature in the hot metal desulfurization process was lower due to the preceding dephosphorization process in the torpedo car. Hence, a new technique, which can enhance desulfurization efficiency under the condition of lower hot metal temperature, was needed.

Many studies concerning the effect of hot metal temperature⁵ and mixing energy⁶ on hot metal desulfurization efficiency have been reported. In this work, utilization of a reducing gas, namely, propane gas, was examined, focusing on the desulfurization reaction. Thermodynamically, a lower oxygen potential has the effect of enhancing the desulfurization reaction. Several studies⁷–¹¹ have reported the effect of aluminum as a reducing agent in hot metal desulfurization. However, only a few reports concerning the effects of reducing gases¹²–¹⁴ have been published.

In this work, 4 ton-scale pilot plant tests were carried out in order to simulate CaO-based flux injection in the hot metal desulfurization process. The effect of propane gas mixing with a nitrogen carrier gas on desulfurization efficiency was evaluated in pilot-scale tests, and commercial-scale tests were then carried out with a torpedo car. After the evaluation in the actual torpedo car tests, propane gas mixing equipment was installed at JFE Steel’s East Japan Works (Chiba District). After that, JFE Steel adopted the mechanical stirring method by an impeller in the hot metal desulfurization process¹⁵ as a substitute for torpedo car injection.¹⁵ Therefore, application of propane gas to the mechanical stirring process was also investigated in 4 ton-scale experiments, and a propane gas system was installed at the commercial-scale plants.
2. Experimental Procedures

2.1. Flux Injection

2.1.1. 4 ton-scale Pilot Plant Tests

Figure 1 shows a schematic illustration of the 4 ton-scale low frequency induction furnace used in the pilot plant tests.\(^4\) The inner size and depth of the furnace are 0.92 m × 1.44 m, respectively. The hot metal depth in the furnace is 0.90 m with 4 tons of hot metal. The experimental conditions are shown in Table 1. An injection lance, which is caught with a refractory, is immersed in the hot metal, and CaO-based flux (70CaCO\(_3\)-22CaO-3CaF\(_2\)-5C/wt%; average size: 125 μm\(^1\)) is injected with a nitrogen carrier gas. The propane gas is mixed with the nitrogen carrier gas. Top slag is perfectly skimmed in advance, and the hot metal temperature is controlled within 3 K. The induction power is off during flux injection. Adequate hot metal samples are taken and analyzed to evaluate the desulfurization rates. An oxygen sensor (Heleus Electronite) is immersed at specific points in the hot metal to evaluate the oxygen potential in the hot metal.

2.1.2. Commercial Scale Tests (250–350 ton Torpedo Car)

Figure 2 and Table 2 show a schematic diagram and the conditions of the experiments with the torpedo car. The plumbing for the propane gas was constructed and merged with the existing nitrogen carrier gas line. The new gas supply system has a safety valve and a purge gas introduction function. Nitrogen gas is introduced in the lance while immersing the lance and removing the lance from the hot metal, and propane gas is mixed only when the lance is actually in the hot metal. Hot metal and slag samples are taken and analyzed to evaluate desulfurization efficiency.

2.2. Mechanical Stirring With Impeller

2.2.1. 4 ton-scale Pilot Plant Tests

The apparatus and conditions were shown in Fig. 3 and

<table>
<thead>
<tr>
<th>Hot metal</th>
<th>Weight</th>
<th>250–350</th>
<th>ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lance immersion depth</td>
<td>1.0–1.5</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Flux feeding rate</td>
<td>0.2–0.6</td>
<td>kg/min/t</td>
<td></td>
</tr>
<tr>
<td>Carrier gas flow rate</td>
<td>(\text{N}_2)</td>
<td>30</td>
<td>NL/min/t</td>
</tr>
<tr>
<td></td>
<td>(\text{C}_3\text{H}_8)</td>
<td>3.7–7.4</td>
<td>NL/min/t</td>
</tr>
</tbody>
</table>

Table 2. Experimental conditions of torpedo car tests.

<table>
<thead>
<tr>
<th>Initial conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>[%C]</td>
</tr>
<tr>
<td>[%Si]</td>
</tr>
<tr>
<td>[%Mn]</td>
</tr>
<tr>
<td>[%P]</td>
</tr>
<tr>
<td>[%S]</td>
</tr>
</tbody>
</table>

Fig. 1. Experimental apparatus of 4 ton-scale tests.

Fig. 2. Experimental apparatus of torpedo car tests.

Fig. 3. Schematic illustrations of reducing gas blowing in 4 ton-scale experiments.
Table 3, respectively. Both propane gas top blowing and propane gas injection were carried out for comparison. Coke oven gas (H₂/50, CH₄/30, CO/7, balance/13 vol%) was used for comparison with propane gas.

2.2.2. Commercial Scale Tests (350 ton Charging Ladle)

JFE Steel adopted a mechanical stirring method in the hot metal desulfurization process as a substitute for the torpedo car injection method. The technique of propane gas blowing was applied to the mechanical stirring process based on the results obtained by 4 ton-scale experiments.

2.3. Small-scale Hot Metal Experiments

Small-scale experiments were carried out in order to investigate the mechanism of the effect of propane gas on desulfurization. Figure 4 and Table 4 show a schematic diagram and the conditions of the 30 kg-scale hot metal experiments, respectively. A formed and sintered CaO-2%CaF₂ tip is installed at the end of an alumina tube. CaCO₃ was not added in the sintered tip for avoiding decomposition and collapsing. Furthermore, carbon was not added for distinguishing with that decomposed from propane gas. CaF₂ is known as the effective additives to CaO based flux on desulfurization efficiency. Therefore, CaF₂ was added in the sintered tip for observing the same desulfurization behavior as the flux injection in hot metal. The tube is immersed in the hot metal and used for gas bubbling in order to observe the interface of the three phases (hot metal, CaO-2%CaF₂, and gas). CaO-2%CaF₂ powder is ground to under 100 meshes, formed, and burned in the air at a temperature of 1473 K. After gas bubbling for 5 minutes, the tip of CaO-2%CaF₂ is mounted and polished as a specimen for SEM, EPMA, and Micro-XRD.

3. Experimental Results

3.1. Flux Injection

3.1.1. 4 ton-scale Pilot Plant Tests

Figure 5 shows the change of the [S] content as a function of desulfurization flux consumption. Desulfurization behavior seems to obey the first-order reaction. At the same flux supply rate, the flux efficiency for desulfurization increased with higher propane gas flow rates. Figure 6 shows the relationship between the concentration of propane gas and the measured oxygen potential near the outlet of the lance. The oxygen gas concentration was calculated from the gas flow rates of nitrogen and propane and CO₂, which can be calculated from the supply rate of CaCO₃ under an assumption of perfect and immediate decomposition of CaCO₃ in the hot metal (CaCO₃→2CO). The oxygen
potential in the hot metal near the outlet of the injection lance is reduced by introducing propane gas.

3.1.2. Commercial Scale Tests (250–350 ton Torpedo Car)

Figure 7 shows the effect of propane gas mixing on the desulfurization rate. The horizontal axis indicates the degree of desulfurization, and the slope is equal to the apparent rate constant of desulfurization. Desulfurization efficiency increases with propane gas injection. The difference in the propane gas flow rates (3.7, 7.4 Nl/min/t) does not have a clear effect on desulfurization efficiency. The flux efficiency for desulfurization increased by 1.2–1.3 times with mixing of propane gas with the nitrogen carrier gas at a propane gas ratio of 10–20%. Figure 8 shows the relationship between the slag basicity and the sulfur partition ratio between the slag and hot metal. The sulfur partition ratio was increased by 1.5–3.0 times with propane gas mixing. When the propane gas mixing equipment was installed at East Japan Works, consumption of desulfurization flux decreased by 20% compared with the case without propane gas.

3.2. Mechanical Stirring With Impeller

3.2.1. 4 ton-scale Pilot Plant Tests

The desulfurization behaviors are shown in Fig. 9. The desulfurization rate increased with propane gas compared with coke oven gas and without reducing gas. Furthermore, the desulfurization rate with top-blowing propane gas was higher than that with propane gas injection. In this experiment, the oxygen potentials with top-blowing propane gas decreased and consequently, the sulfur partition ratio between the slag and metal increased with top-blowing propane gas. The hydrogen contents in the hot metal were 3–8 ppm, which were higher than those in the case without propane gas (1 ppm). During stirring at the rotation speed of 250 rpm, it was observed that the vortex height at the wall of the furnace increased from 110 to 140 mm with top-blowing propane gas, as shown in Fig. 10. The vortex height is defined as the distance between the hot metal level at the wall of the furnace without stirring and with stirring. From the result in Fig. 10, the higher vortex height at 250 rpm obtained by top-blowing propane gas is equivalent with that at 300 rpm without top-blowing propane gas, which means the stirring energy is increased by the top-blowing propane gas.

3.2.2. Commercial Scale Operation (350 t Charging Ladle)

Top-blowing propane gas equipment has been installed at JFE Steel’s East Japan Works and West Japan Works. Consumption of desulfurization flux was reduced by 20% by adopting the top-blowing propane gas technique. The reduction of the oxygen potential in the hot metal by the top-blowing propane gas and its effect on the sulfur partition ratio are shown in Fig. 11. The sulfur partition ratio with mechanical stirring was higher than that with flux injection in a torpedo car at the same oxygen potential level with utilizing propane gas. In the case of mechanical stirring, the hot metal temperatures were in the range between 1 523 and 1 573 K.
The sulfur partition ratio with mechanical stirring was higher than the calculated value, which was caused by contamination by sulfur in the remaining slag and carried over slag. A 16% reduction in the cost of desulfurization flux has been achieved, even considering the cost of the propane gas.

3.3. Small-scale Hot Metal Experiments

Figure 12 shows the EPMA mapping images. In the case of Ar gas bubbling shown in (a), sulfur-enriched islands and iron penetration were observed. In the case of propane gas bubbling in (b), a thick layer and many islands of sulfur-enriched regions were observed. With propane gas bubbling, the iron penetration layer was thicker than with Ar gas bubbling. Sulfur-enriched islands and a sulfur-enriched layer were detected as CaS through Micro-XRD analysis. Fluorine distribution was not observed clearly, since its lower concentration in the flux. Figure 13 shows schematic illustrations of the observed and analyzed results of the small-scale experiments. In the case of Ar gas bubbling, sulfur-enriched islands were observed at the tip of the sintered flux. In the case of hydrogen gas bubbling, a sulfur-enriched layer was observed at the tip, and small cracks (100–500 μm) were detected at the outer layer of the sintered flux. In the case of propane gas bubbling, a thicker sulfur-enriched layer at the tip and side, many small cracks (10–100 μm), and dispersion of fine carbon particles (10 μm) were observed. From these results, hydrogen and carbon, which are generated by decomposition of propane gas, create fine cracks at the interface with CaO particles. Especially, finer cracks can be made with fine carbon particles, which are generated by the propane gas decomposition. In the case of flux injection, the CaO particles are in the range of 10–300 μm, and propane gas can decompose at the outlet of the injection lance. Therefore, the same phenomenon as observed in the small-scale experiments can occur in the case of flux injection with propane gas mixing. The interfacial area between the CaO and hot metal can be increased by the aforementioned small cracks.

4. Discussion

4.1. Effect of Propane Gas on Oxygen Potential in Hot Metal

First, the oxygen potentials in the hot metal measured by the oxygen probe are compared with the values calculated thermodynamically. The calculation is based on the following assumptions:

1) Equilibrium of Eqs. (1)–(5) is established at the interface between the hot metal and gas phase.
2) Propane gas perfectly and immediately decomposes into carbon and hydrogen.
3) The total pressure in the gas phase is 1 atm (CO, CO₂, H₂, H₂O, O₂).
4) The soluble elements in the hot metal are [C], [H], and [O].

\[
\frac{1}{2} O_2(g) = [O] \quad \cdots \quad (1)
\]

\[
[C] + [O] = CO(g) \quad \cdots \quad (2)
\]

\[
[C] + CO_2(g) = 2CO(g) \quad \cdots \quad (3)
\]

\[
H_2(g) = 2[H] \quad \cdots \quad (4)
\]

\[
2[H] + [O] = H_2O(g) \quad \cdots \quad (5)
\]

The above assumption 2) is expressed by Eq. (6).

\[
C_3H_4(g) = 3C + 4H_2(g) \quad \cdots \quad (6)
\]

Equations (7)–(13) are realized by assumption 1).

\[
\log K_{(1)} = a_o / P_{O_2}^{0.5} = 6120 / T + 0.177 \quad \cdots \quad (7)
\]

\[
\log K_{(2)} = P_{O_2} / (a_o \cdot A_o) = 1160 / T + 2.003 \quad \cdots \quad (8)
\]

\[
\log K_{(3)} = P_{O_2} / (a_o \cdot P_{H_2}) = -7558 / T + 6.756 \quad \cdots \quad (9)
\]

\[
\log K_{(4)} = a_H / P_{H_2} = [\%H]^2 / P_{H_2} = 1906 / T - 1.591 \quad \cdots \quad (10)
\]

\[
\log K_{(5)} = P_{H_2O} / (a_o \cdot a_H^2) = 10620 / T + 0.114 \cdots \quad (11)
\]

Equation (12) is realized by assumption 1).

\[
P_{CO} + P_{CO_2} + P_{H_2} + P_{H_2O} + P_{O_2} = 1 \quad \cdots \quad (12)
\]

Equation (13) can be obtained as the quadratic equation of \( a_o \) by Eqs. (7)–(12), where \( A, B \) and \( C \) are expressed by Eqs. (14), (15), and (16), respectively.

\[
A = \left[ \frac{1}{\log K_{(1)}} \right] + \left[ \frac{a_o \cdot \log K_{(3)}^2}{\log K_{(3)}} \right] \quad \cdots \quad (13)
\]

\[
B = a_o \cdot \log K_{(3)} + [\%H] \cdot \log K_{(5)} \quad \cdots \quad (14)
\]

\[
C = \left[ \frac{[\%H]^2}{\log K_{(4)}} \right] - 1 \quad \cdots \quad (15)
\]

The propane gas concentration in the carrier gas is fixed by the injection conditions in order to calculate the oxygen potential in the hot metal. Propane gas decomposes into hydrogen as shown in Eq. (6), and the partial pressure of hydrogen, \( P_{H_2} \), can be calculated from the flow rates of the propane and nitrogen gases. The activity of soluble hydrogen, \( a_H (=[%H]) \), can be calculated from Eq. (10) using \( P_{H_2} \). Five unknown elements, \( i.e., \) the partial pressures of CO, CO₂, H₂O, and O₂, and \( a_o \) can be solved using the five Eqs. (7)–(9), (11) and (12). \( a_o \) can be obtained from \( a_H \) and \( a_o \) (= 28.2). Figure 14 shows a comparison between the observed and calculated values of \( a_o \), which are in good agreement. In Fig. 14, ① and ② show the conditions with and without propane gas in the torpedo car experiments. The relationship between the oxygen potential in the hot metal and the sulfur partition ratio between the slag and hot metal, \( L_s \), at the end of desulfurization is shown in Fig. 15. The oxygen potentials in torpedo car injection were calculated using ① and ② in Fig. 14. The equilibrium sulfur partition ratio between the slag and metal, \( L_s \), was calculated with Eqs. (7) and (17)–(19), where the sulfide capacity, \( C_s' \), was extrapolated with the data \( (C_s^2) \) of a CaO–CaF₂ system at 1773 K and its temperature dependence. The results show that \( L_s \) is increased by propane gas mixing. Consequently, the observed \( L_s \) values are lower than the calculated ones for both the 4 ton-scale experiment and the torpedo car test. In the hot metal desulfurization process, the observed \( L_s \) tends to be lower than the calculated value, since the injected CaO-based flux is in a solid state. However, the oxygen potential in the hot metal near the lance outlet is presumed to decrease with propane gas mixing. Consequently, the observed \( L_s \) increased as the oxygen potential in the hot metal decreased, thus showing the same trend as the theoretical values.

\[
\log L_s = \log C_s' + \log f_s - \log a_o \quad \cdots \quad (17)
\]

\[
\log C_s' = \log C_s^{2-} - 769 / T + 1.30 \quad \cdots \quad (18)
\]

\[
\log C_s^{2-} = -1.45 - 0.00333 \times (1773-T) \quad \cdots \quad (19)
\]

The desulfurization rate in the 4 ton-scale experiments was evaluated as follows. The consumption of desulfurization flux can be assumed to correspond to the injection time at the same flux supply rate. The desulfurization rate can be expressed as Eq. (20) assuming that the rate-controlling step is the mass transfer rate in hot metal. The apparent rate constant, \( K_s \), is expressed as Eq. (21) assuming that \([S] = [S]_i\).
4.2. Effect of Propane Gas on Improving Desulfurization Efficiency

Franz et al.\cite{Franz} and Noll et al.\cite{Noll} reported the effect of bubbling gas on hot metal desulfurization in 25 kg and 1.5 ton-scale experiments. In the 25 kg-scale experiment, the desulfurization rate with addition of a desulfurization flux at a rate of 10 kg/t and methane gas bubbling at 3 Nl/min is three times larger than those with Ar and CO gas bubbling under the same conditions. The influence of methane gas was explained by the fact that [C] and [H] act as reductants. Yagi et al.\cite{Yagi} examined the desulfurization behaviors in various atmospheres, and found that the desulfurization rate in a natural gas atmosphere increased by three times in comparison with those in Ar and CO gas atmospheres. Moreover, Moore et al.\cite{Moore} investigated the deoxidation of molten steel with a top-blowing natural gas (94% methane gas) at 9 Nl/min in a 25 kg-scale experiment. When the oxygen content in the molten steel was more than 160 ppm, the deoxidation reaction proceeded without carbon pickup from the natural gas. The effects of hydrocarbon gases on deoxidation of molten steel and improvement of the desulfurization reaction have been reported. However, the mechanism has not yet been clarified in detail.

In this work, the measured oxygen potentials at the outlet of the injection lance decreased with propane gas injection, and were in agreement with the values calculated thermodynamically based on the equilibrium between gas and hot metal. The equilibrated [S]e with those oxygen potentials were 0.00008% with propane gas and 0.0002% without propane gas, respectively, which indicates that the driving force for desulfurization reaction rate is small. Therefore, the effect of propane gas on improving the desulfurization rate cannot be explained only by a driving force, which equals the difference between the [S] level and [S]e.

At around 573 K, propane gas decomposes as shown in Eq. (6), and many small carbon particles are observed in dense sintered desulfurization flux, as shown in Fig. 13. Hence, propane gas decomposes at the interface of three phases, i.e., the hot metal, desulfurization flux, and gas, and generates carbon. As shown in Fig. 12, the sulfur-enriched layer was thicker in the case of propane gas bubbling than that in the case of Ar gas bubbling. In the case of propane gas bubbling, many cracks were observed in the sintered desulfurization flux, and the penetration layer of the hot metal into the sintered flux was thicker than that in the case of Ar gas. From these results, it is supposed that the existence of fine carbon particles and hydrogen, which are generated by decomposition of propane gas, increases the interfacial area between the hot metal and the desulfurization flux. Many iron particles were observed at the tip of sintered flux as shown in Fig. 12. That indicates that the interfacial area between hot metal and flux is increased by propane gas. The mechanism of the effect can be assumed by the following mechanism.

1) Hydrogen and propane gas react by Eqs. (4) and (6) and locally cools mainly at the tip of sintered flux, that generates the fine cracks through a thermal stress caused by a local temperature difference.

2) The fine carbon particles decomposed from propane gas immerse into the fine cracks.

3) Aforementioned fine carbon particles immersed into the flux locally expand and break the flux.

4) CaS generates at the tip of sintered flux and locally expands and breaks the flux.

In the 4 ton-scale tests, the effect of coke oven gas on desulfurization was lower than that of propane gas. The main element of the coke oven gas is hydrogen (50 vol%), which can be assumed as the same phenomenon in the case of hydrogen gas bubbling. Hence, one of the differences of the effect on desulfurization can be considered by the difference of the interfacial area based on the observation result in Fig. 13.

4.3. Effect of Propane Gas on Desulfurization With Mechanical Stirring

In the case of top-blowing propane gas application to the
mechanical stirring method, the effect of enhancing the stirring energy was found in addition to both reducing oxygen potential and increasing the interfacial area between flux and hot metal. The vortex height was increased by top-blowing propane gas as shown in Fig. 10. Many holes were observed in hot metal samples in the case of top-blowing propane gas. These holes are presumed to be generated by formation of hydrogen gas bubbles in the hot metal. \([H] \) calculated by the amount of propane gas is 286 ppm. On the other hand, the saturated hydrogen content in the hot metal can be calculated as 14 ppm. \(^{17}\) Therefore, it can be estimated that hydrogen bubbles easily form in the hot metal as a result of the hydrogen supply from the top-blowing propane gas. The density of hot metal which contains many bubbles should be lower than that of hot metal without bubbles. Therefore, at the same impeller rotation speed, the stirring energy is higher with top-blowing propane gas due to the reduced density of the hot metal near the surface. The flame generated by propane gas combustion was absorbed into the hot metal at the cavity created by impeller rotation. As a result, \([H] \) in the hot metal increased from 1 ppm to 3–8 ppm with top-blowing propane gas. In contrast to this, when the propane gas was injected directly into the melt, many splashes of metal were observed from the hot metal surface. From this, it is estimated that propane gas bubbling interrupts (disrupts) the hot metal flow generated by impeller mixing.

5. Conclusions

Application of propane gas blowing to hot metal desulfurization was investigated in 30 kg-scale and 4 ton-scale experiments and commercial plant tests. The conclusions are summarized as follows.

(1) In the 4 ton-scale experiment, the flux efficiency for desulfurization at a flux feeding rate of 0.25 kg/min/ton increased by 1.7 times with mixing of propane gas with the nitrogen carrier gas at a propane gas ratio of 58%.

(2) The oxygen potential in the hot metal decreased from \(10^{16} \) to \(10^{18} \) atm by mixing propane gas in the nitrogen carrier gas at a propane gas ratio of 30%. These oxygen potentials are equivalent to the equilibrium values with the gas phases.

(3) In a commercial-scale test with a torpedo car, the flux efficiency for desulfurization increased by 1.2–1.3 times with mixing of propane gas with the nitrogen carrier gas at a propane gas ratio of 10–20%. The sulfur partition ratio between the slag and hot metal increased by 1.5–3.0 times by mixing propane gas with the nitrogen carrier gas under that condition.

(4) The effect of propane gas mixing on improvement of desulfurization efficiency is presumed to be caused by a decrease in the local oxygen potential, together with an increase in the interfacial area between the hot metal and flux due to the existence of fine carbon particles decomposed from the propane gas.

(5) A top-blowing propane gas technique was adopted in a commercial hot metal desulfurization operation by mechanical stirring with an impeller. As a result, desulfurization flux consumption was reduced by 20% with top-blowing propane gas. The flame generated by propane gas combustion was absorbed into the hot metal at the cavity created by impeller rotation. As a result, \([H] \) in the hot metal increased from 1 ppm to 3–8 ppm with top-blowing propane gas. The presumed effects of the top-blowing propane gas are reduction of the oxygen potential in hot metal and enhancement of stirring energy due to an increase of the vortex height at the same rotation speed. The sulfur partition ratio between the slag and hot metal with mechanical stirring was higher than that with flux injection in a torpedo car at the same oxygen potential level with utilizing propane gas.

Symbols

\[
\begin{align*}
\text{Cs} & : \text{Cs}^\prime, \text{Cs}^\prime_2: \text{Sulfide capacity} \\
\text{Pi} & : \text{Activity coefficient of sulfur in hot metal} \\
K & : \text{Equilibrium constant} \\
K_a & : \text{Apparent desulfurization rate constant per unit consumption of desulfurization flux (kg/t)}^{13} \\
L_\text{s} & : \text{Sulfur partition ratio between slag and hot metal} \\
P_i & : \text{Partial pressure of } i \text{ in gas phase (atm)} \\
[S] & : \text{Equilibrium sulfur content in hot metal (mass\%)} \\
T & : \text{Temperature (K)} \\
W_{\text{flu}}, \text{Consumption of desulfurization flux (kg/t)} & \\
\end{align*}
\]

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