

RESEARCH ON LADLE NOZZLE CLOGGING DURING CONTINUOUS CASTING OF NON-ORIENTED ELECTRICAL STEEL WITH HIGH SILICON

To figure out the reason causing ladle nozzle clogging during CC (continuous casting) of a non-oriented electrical steel with high silicon (or HNO for short) and get a method to address it, this paper studied the theoretical calculation of flow rates during CC, the inclusions around the slide gate where ladle nozzle clogging happened, and Ca-treatment at the end of RH for decreasing ladle clogging of the electrical steel both theoretically and practically. The results showed that: The bigger diameter of a nozzle or less nozzle clogging can guarantee an enough flow rate for reaching the target casting speed. Ladle nozzle clogging can be predicted by comparing the percentage of slide gate opening. Al_2O_3 and its composite inclusions were the main reason that caused the ladle nozzle clogging of the electrical steel. Higher [Al] or TO will increase the amount of Pure Ca wires for Ca-treatment. The results of the verification tests fit the thermodynamic calculation, and Ca-treatment using pure Ca wires could prevent ladle nozzles from clogging without affecting the magnetic properties of the electrical steel.

Keywords: Electrical Steel; Ladle Nozzle; Clogging; CC

1. Introduction

Because of nozzle clogging, a casting speed usually decreased, and even an whole casting would be canceled in some severe cases. The clogging of submerged entry nozzles has been studying for years, and it was believed that nozzle clogging usually occurred due to inclusions aggregating [1-6]. However, there has been a little research on ladle nozzle clogging, and no a research on it about electrical steel. Moreover, there has been being ladle nozzle clogging during CC of electrical steel, which is deoxygenated by aluminium alloys. And electrical steel has unique properties and its production process are more complicated compared to other steel [7-9]. Therefore, it is necessary to study what causes ladle nozzle clogging during casting electrical steel, work out a effective way to solve the problem, which will not decrease the magnetic properties of electrical steel. This paper studied the theoretical calculation of flow rates that could affects ladle nozzle clogging of the HNO, what inclusions causing the ladle nozzle clogging, the effect of Ca-treatment on addressing the ladle nozzle clogging of the HNO both theoretically and practically without reducing the magnetic properties.

2. Experimental methods

The paper studied the ladle nozzle clogging of HNO, whose chemical composition is shown in Table 1. The production pro-

cess was BOF → RH → CC. Clogging at the SEN (submerged entry nozzle) in the tundish was not considered, because clogging at the SEN was very slight compared to clogging at the ladle nozzle in this mill.

TABLE 1

The chemical composition of HNO after CC (in mass%)

Elements	C	Si	Mn	S	Al	N
mass%	≤0.003	2.6-3.0	0.25~0.35	≤0.003	0.40-0.60	≤0.004

The dimension of the slide-nozzle system and the shroud system under a ladle in this research could be seen in Figure 1. A slide gate was used to control the flow rate of liquid HNO poured from a ladle. And a slide gate was made of Al_2O_3 -C bricks, and the bricks at the upper nozzles were high- Al_2O_3 .

The dimension of the ladles was 3800 mm (the diameter of the tops) × 3200 mm (the diameter of the bottoms) × 4006 mm (the height), and their capacity was 2.1×10^6 kg. The side walls and bottoms of the ladles were made of Al_2O_3 -MgO-C bricks, and the bricks at the slag-lines were MgO-C.

The thickness of a top slag was around 80mm during RH, and the slag composition is shown in Table 2. Pure aluminum particles for removing [O] from liquid HNO were put into a ladle during RH.

When ladle nozzle clogging happened in a casting with 10 heats, then the samples of the solid HNO in the nozzles were

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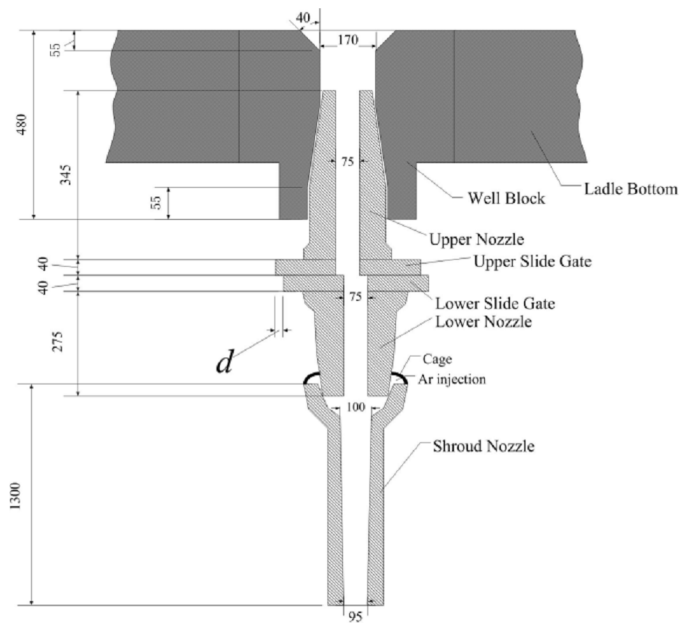


Fig. 1. The dimension of the slide-nozzle system and the shroud system

TABLE 2

The composition of slag after BOF tapping and before RH process (in wt%)

Components	CaO	SiO ₂	MgO	TFe	P ₂ O ₅	R
wt%	45 ~ 48	10 ~ 15	6 ~ 10	15 ~ 20	1 ~ 3	2 ~ 5

taken after CC, as shown in Figure 2. From Figure 2(a), it can be seen that the edge of a cross section near the top of the solid HNO was a smooth circle, which indicated there was no apparent clogging in the upper nozzle. However, there were some obvious loose areas with lots of inclusions and holes around the slide gate, especially close to the corner between the upper slide gate and the lower one, as shown in Figure 2(b). The remaining solid HNO in the nozzles was cut into small samples to be studied, whose sampling method could be seen in Figure 3, which is a part of Figure 2(b). The types, the shapes, the sizes and the distribution of inclusions in the solid HNO samples, which might bring the ladle nozzle clogging were analyzed by using SEM and EDS.

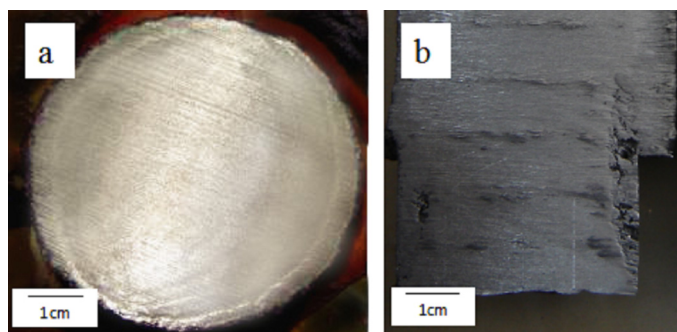


Fig. 2. The samples after casting: (a) a cross section near top of the solid steel in the nozzles, (b) a part around the slide gate of a longitudinal section of the solid HNO

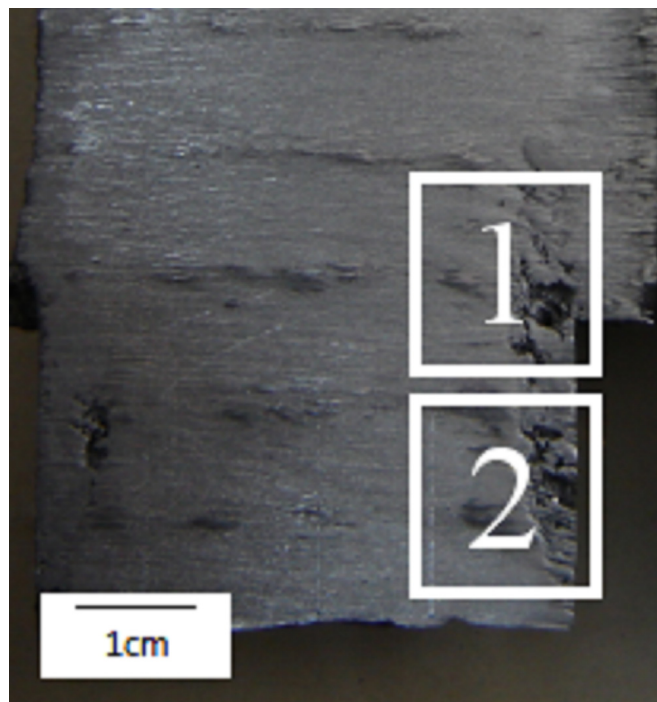


Fig. 3. The sampling method (the samples cut from the white boxes)

In order to modify some properties of inclusions and reduce the clogging, Si-Ca wires or pure Ca wires were into liquid HNO at the end of an RH process by using a feeding machine, which had two feeding throats, and the feeding speed was 200 m/min. After Ca-treatment, a soft bubble-stirring was being applied for 10 min, and tried to find out the better Ca-treatment. The chemical composition of the Si-Ca wires and pure Ca wires could be seen in Table 3.

TABLE 3

The composition of Si-Ca wires (in wt%)

Elements	Si	Ca	C	Al	P	S
wt%	55.0-65.0	≥26.0	≤1.00	≤2.40	≤0.04	≤0.05

Theoretical calculation of flow rates during CC for analyzing ladle nozzle clogging and thermodynamic calculation of Ca-treatment for guiding Ca-treatment practices were also done.

3. Theoretical calculation of flow rates during CC

Supposing that the slide gate is fully open, a theoretical flow rate of liquid HNO during CC can be calculated by the following Equation [10]:

$$Q_{mass} = \frac{\pi \rho_l D_n^2}{2} \sqrt{\frac{3agh}{6+af}} \quad (1)$$

where Q_{mass} is a flow rate, kg/s. ρ_l is the density of liquid HNO, 7000 kg/m³ for this study. D_n is the diameter of a nozzle, 0.075 m for practical casting. a is a constant, 1 for the turbulent flow studied. g is the acceleration of gravity. h is the height of

the liquid level of rest HNO from the bottom of a ladle, m. f is a friction loss factor, 0.5 for this case.

A flow rate through nozzles (Q_{mn}) can be calculated by Equation (2).

$$Q_{mn} = \frac{wt\rho_s}{30} S_c \quad (2)$$

where w and t are respectively the width and the thickness of a slab, 1.3 m and 0.23 m for this study. ρ_s is the density of solid HNO, 7600 kg/m³ for the case. S_c is a casting speed for two strands, 1.0 m/min for the target of this case. Therefore, based on Equation (2), Q_{mn} should be 75.75 kg/s, 5.13 t/min, for reaching the target casting speed in the case of the CC with two strands.

Based on Equation (1) and Equation (2), as shown in Figure 4, an increase of a flow rate is associated with a decrease of the height of a liquid level. And if a height decreased from 4 m to 1.5 m, there will be a around 50 percent reduction in the flow rate. It can be shown that the bigger diameter of a nozzle means a higher flow rate and casting speed. If a nozzle diameter was 90 mm, even though a height was obviously below 0.5 m, such as 0.25 m, the casting speed can still reach the target of 1.0 m/min. However, if a nozzle diameter was 60 mm, even though a height was 0.75 m, three times of the height above, the casting speed will not reach the target (only 0.98 m/min, i.e. 72.87 kg/s). It can be indicated that the bigger diameter of a nozzle could effectively produce an enough flow rate for casting.

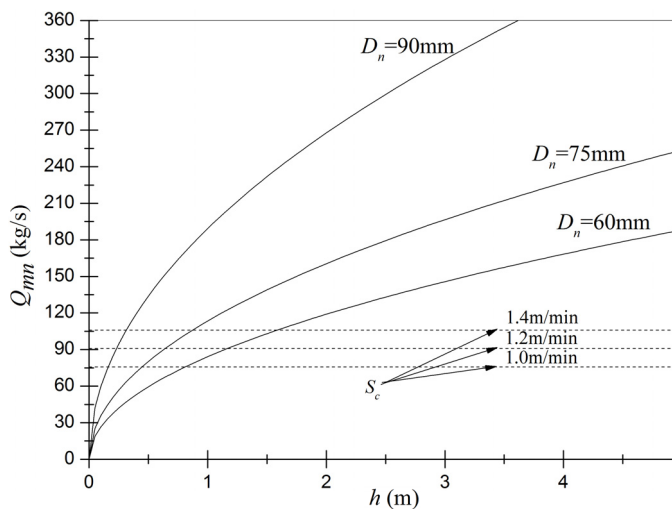


Fig. 4. The relationship between Q_{mn}/S_c and h during casting

The theoretical flow rate determined by a percentage of a slide gate opened, i.e. Q_{mn} in kg/s, can be calculated by Equation (3):

$$Q_{mn} = p_{go} Q_{mass} \quad (3)$$

where p_{go} is the percentage of a slide gate opened, which can be calculated by the following Equation:

$$p_{go} = \frac{A}{\pi \left(\frac{D_n}{2}\right)^2} = \frac{2}{\pi} \left(\arccos \frac{d}{D_n} - \frac{d}{D_n^2} \sqrt{D_n^2 - d^2} \right) \quad (4)$$

where A is the area of a slide gate opened, m². d is a distance that the lower slide gate moves, m, as shown in Figure 1. Based on Equation (4), as shown in Figure 5, it can be easily seen that with the movement of a slide gate, the slide gate would open bigger and bigger. And a smaller diameter of a nozzle must move more to open the same degree of a bigger one.

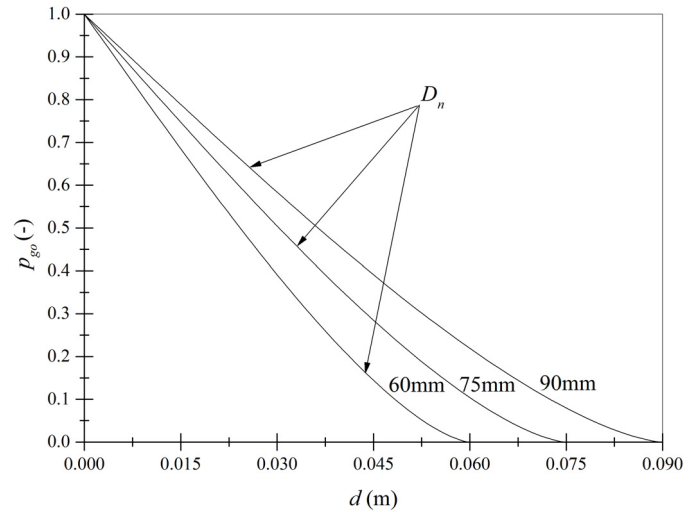


Fig. 5. The relationship between p_{go} and d during casting

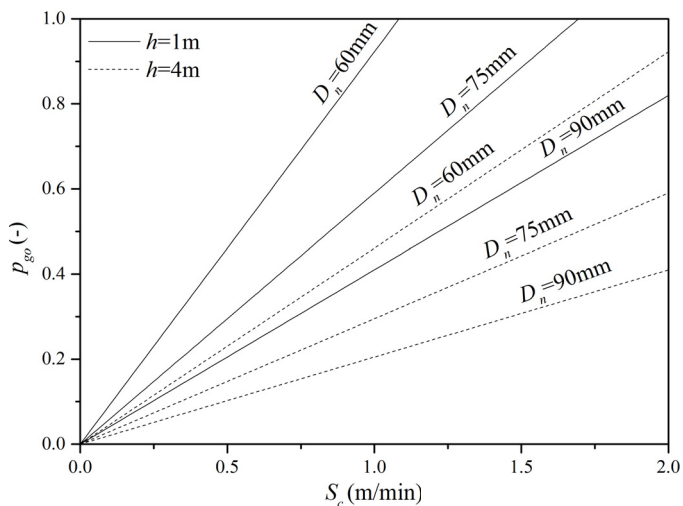
Based on Equation (1), Equation (2) and Equation (3), Equation (5) can be deduced:

$$p_{go} = \frac{wt\rho_{sl}S_c}{15\pi D_n^2} \sqrt{\frac{6+af}{3agh}} \quad (5)$$

where $\rho_{sl} = \rho_s/\rho_l$. Plug the values of the variables for this study, as shown above, into Equation (5), and it can be reduced to Equation (6):

$$p_{go} = 3.24 \times 10^{-3} \frac{S_c}{\sqrt{h} D_n^2} \quad (6)$$

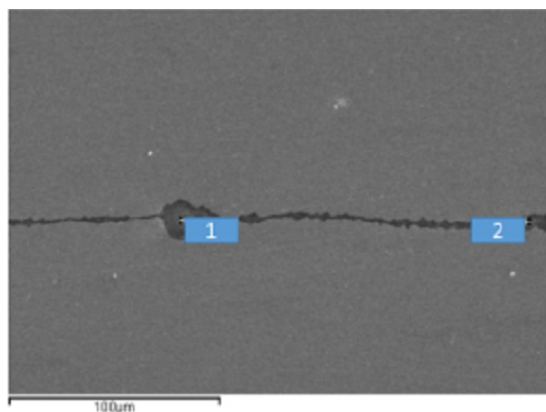
Based on Equation (6), the relationship among p_{go} , S_c , D_n and h are shown in figure 6. If the diameter of a nozzle was 90 mm and the liquid level of rest HNO is 4 m (at the beginning of a casting), the slide gate that opens 20% can lead to the target casting speed of 1.0 m/min. As the liquid level of rest steel decreases to 1 m, the slide gate must move to open 40% (two times of the beginning) for reaching 1.0 m/min. If a nozzle was clogged to a smaller diameter such as 60 mm and the liquid level of rest steel is 1m, almost the fully opened slide gate can meet the demand of 1.0 m/min. However, as the liquid level of rest HNO decreases to 0.5m, for $D_n = 60$ mm, even the 100% of slide gate can not generate the target speed. And at the same time, in order to keep a steady liquid level in the tundish, the casting speed has to be decreased. From Figure 6, for a fixed slide gate diameter, the appropriate p_{go} that can maintain different casting speeds could be figured out. Such as $D_n = 75$ mm for the practical case with the casting speed of 0.8 m/min or 1.2 m/min, the p_{go} at least is supposed to be 23.04% or 34.56% for maintaining

Fig. 6. The Relationship among p_{gg} , S_c , h and D_n

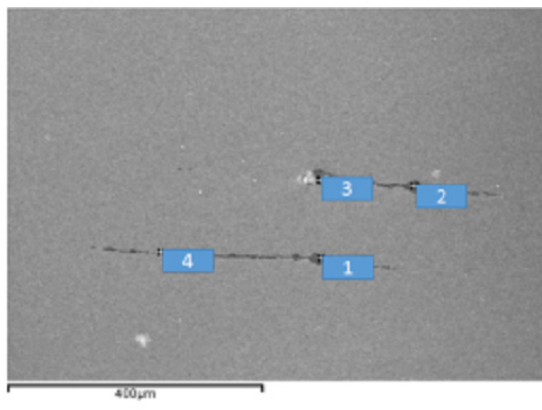
sufficient liquid steel in the tundish. It can be indicated that if the actual value of p_{ct} was being higher than the theoretical one, then clogging in the ladle nozzle have been happening.

4. Inclusions observation and analysis

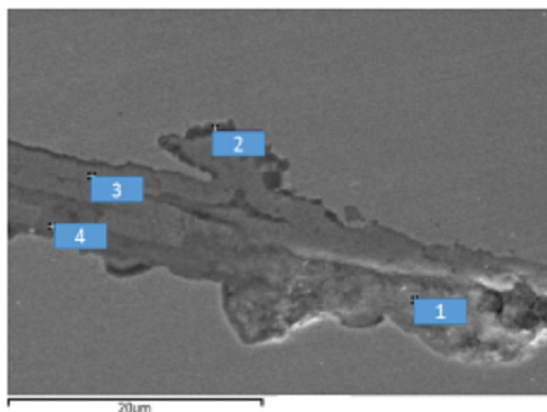
As shown in Figure 7, most of inclusions were the ones containing Al_2O_3 , and distributed alone or like a chain. There are also a small number of pure Al_2O_3 inclusions and CaO inclusions. The composite inclusions were irregular, and their sizes were big, even as large as a few centimeters shown in Figure 7. It was believed that those inclusions were generated from adding the Al (deoxidation and extra Al for meeting performance requirements of the HNO) by using pure Al, and from the reaction between Al_2O_3 and slag/furnace lining bricks, whose



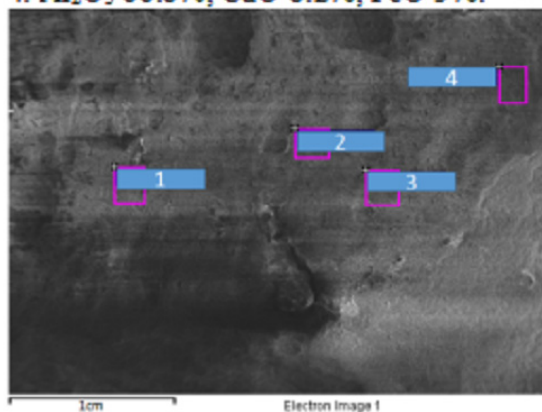
1: Al_2O_3 83.2%, CaO 5.2%, MnO 3.0%,
 MgO 3.5%, FeO 5.1%.
 2: Al_2O_3 86.8%, CaO 9.4%, FeO 3.8%.



1: Al_2O_3 89.7%, CaO 7.0%, FeO 3.3%.
 2: Al_2O_3 79.6%, CaO 14.5%, FeO 5.9%.
 3: Al_2O_3 81.2%, FeO 8.4%, MgO 10.4%.
 4: Al_2O_3 88.8%, CaO 8.2%, FeO 3%.



1: Al_2O_3 76.7%, CaO 6.0%, MnO 2.3%,
 MgO 10.4%, FeO 4.6%.
 2: Al_2O_3 35.5%, CaO 3.1%, MgO 3.7%,
 FeO 57.7%.
 3: Al_2O_3 41.2%, CaO 3.6%, MgO 5.1%,
 FeO 49.9%.
 4: Al_2O_3 80.2%, CaO 13.6%, MgO 2.1%,
 FeO 4.1%.



1: Al_2O_3 89.6%, CaO 7.5%, FeO 2.9%.
 2: Al_2O_3 88.9%, CaO 7.5%, FeO 2.6%.
 3: Al_2O_3 87.5%, CaO 8.5%, MgO 2.0%,
 FeO 3.9%.
 4: Al_2O_3 81.0%, CaO 14.4%, MgO 2.0%,
 FeO 3.6%.

Fig. 7. Inclusions in the steel around the slide gate

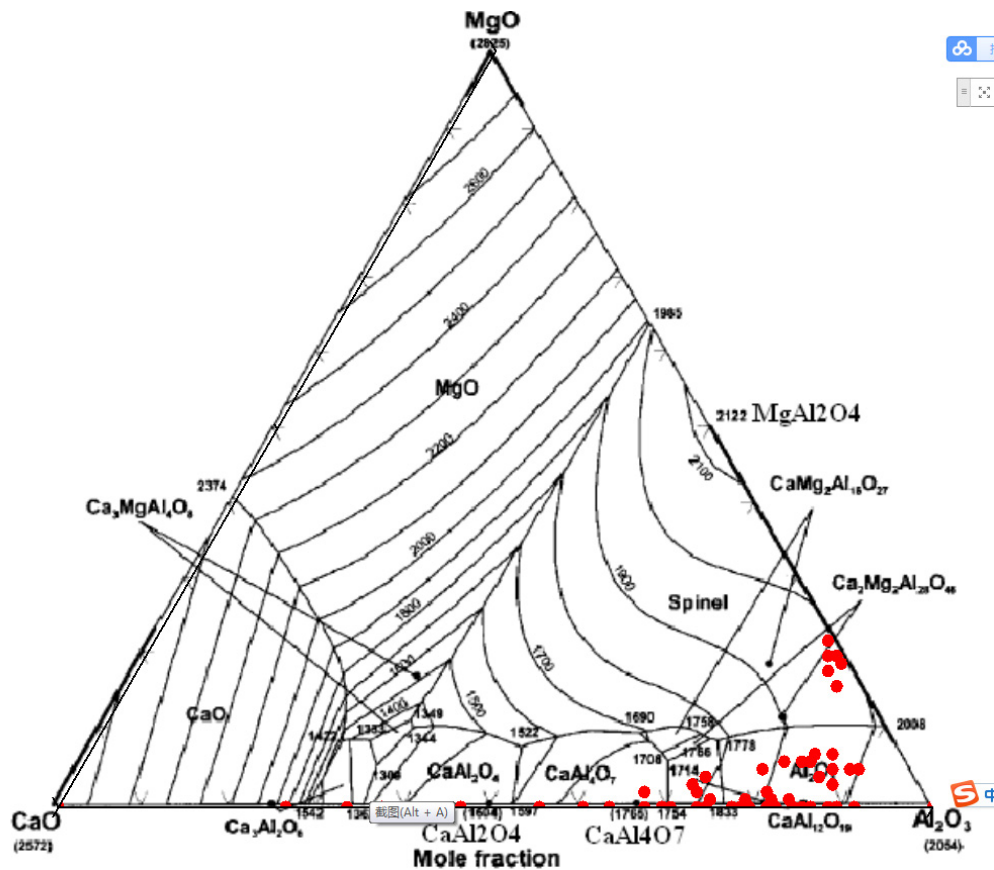


Fig. 8. The inclusions observed in the Al_2O_3 -CaO-MgO diagram with the isograms of the melting points [11]

composition is shown above. It was also noticed that there were some inclusions with a high content of FeO, even as high as 60%. It could be explained that: 1, Severe air absorption consumed local [Al], because of open eyes in a ladle/tundish/mold, a leaky ladle-shroud/submergent-entry-nozzle or etc, and then the oxygen from the air reacted with liquid Fe to form FeO ($2\text{Fe}(l) + \text{O}_2 = 2(\text{FeO})$), during the casting. 2, EDS detected the Fe matrix through a thin inclusion. A higher content of Fe means a higher likelihood of the second reason happening, and a higher content of oxygen was more likely to occur because of the first reason. For reducing the errors caused by the second reason, the FeO content of the inclusions was ignored, and then the inclusions mainly contained $>60\%$ Al_2O_3 , 20 ~ 30% MgO + CaO and other components.

Only Al_2O_3 , CaO and MgO were calculated, the content and the state (liquid or solid) of each inclusion are shown in Figure 8. It could be indicated that almost all the inclusions (97%, 62 of 64) were solid at the casting temperature (1509°C). The melting points of other 2 liquid inclusions at the casting temperature were between 1300°C and 1500°C , with 60% ~ 70% CaO. Most of those inclusions with low melting points would flow away with liquid steel, and not cause the nozzle clogging.

The percentage the inclusions with different CaO/ Al_2O_3 of are shown in Figure 9. From the figure, it could be seen that most of the inclusions are not C12A7 ($12\text{CaO} \cdot 7\text{Al}_2\text{O}_3$), whose melting point is the lowest in CaO- Al_2O_3 inclusions or C3A3($\text{CaO} \cdot \text{Al}_2\text{O}_3$). Therefore, those CaO- Al_2O_3 inclusions with

high melting-points could be transformed into $12\text{CaO} \cdot 7\text{Al}_2\text{O}_3$ by using Ca-treatment, and the nozzle clogging and the final product quality of the HNO will improve.

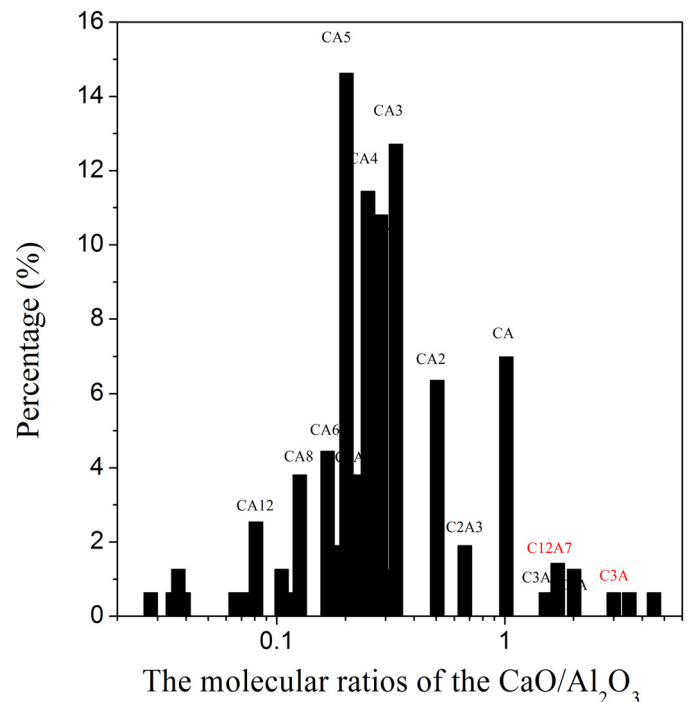
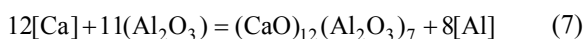


Fig. 9. The percentages of the composite inclusions with different CaO/ Al_2O_3

5. Ca-treatment for preventing ladle nozzle clogging during CC of HNO

5.1. Thermodynamic calculation of Ca-treatment

In this study, only other CaO-Al₂O₃ inclusions → C12A7 was dealt with (because of the lowest melting point in CaO-Al₂O₃ inclusions) by using Ca-treatment. C12A7 created by the reaction of [Ca] plus (Al₂O₃) is shown in Equation (7) [14]:



When the reaction is at equilibrium, the relationship between [Ca] and [Al] will be $[\text{Ca}] = 0.0126\%[\text{Al}]^{2/3}$, and the relationship between [O] and [Al] will be $[\text{O}] = 1.74 \times 10^{-5}\%[\text{Al}]^{-2/3}$, according to the thermodynamic data and the reaction equations [15]. It can be shown that as long as $[\text{Al}]$ is measured before Ca-treatment at the end of RH process, corresponding $[\text{Ca}]$ for generating C12A7 can be got. Too much or too little Ca would create other inclusions with high melting points, and even enough Ca may react with [S] to form (CaS).

Suppose that oxides reacted with [Ca] is only Al₂O₃, and then the rate of Ca in liquid steel (Ca_r , ppm), based on the reaction of Equation (7), can be calculated by Equation (8):

$$\text{Ca}_r = \frac{4M_{\text{Ca}}}{11M_{\text{O}}}(TO - [\text{O}]) = 0.91 \left(TO - 0.174\%[\text{Al}]^{-2/3} \right) \quad (8)$$

Where M_{Ca} and M_{O} are respectively the atomic mass of Ca and O. [O] is dissolved oxygen in liquid steel, ppm. TO is total oxygen, which includes [O] and oxygen in oxides, ppm. Total Ca in steel, in ppm, can be divided into two parts referred to as Ca_r and Ca at equilibrium, in ppm. Therefore, Si-Ca wires or pure Ca wires used for Ca-treatment per heat (m_{Ca} in kg) can be calculated by the following Equation:

$$m_{\text{Ca}} = \frac{C_l}{f \cdot y} \left[1.26 \times 10^{-4}\%[\text{Al}]^{2/3} + 9.10 \times 10^{-7} \left(O_T - 0.174\%[\text{Al}]^{-2/3} \right) \right] \quad (9)$$

Where C_l is the capacity of a ladle, 2.10×10^5 kg for the this study. f is the mass fraction of Ca in a Si-Ca wire or in a pure Ca wire, which is 30% or 96% for the this study. y is the yield of the Ca of a Si-Ca wire or a pure Ca wire in liquid steel. 15 castings (10 heats per casting) were respectively tested with Si-Ca wire treatment or pure Ca wire treatment. During RH, 20 kg of Si-Ca wires or 20 kg of pure Ca wires were added into a ladle. And then y of a Si-Ca wire or a pure Ca wire can be calculated by Equation (10), as shown in Table 4.

$$y = \frac{C_l \text{Ca}_m}{f m_{\text{Ca}}} \quad (10)$$

Where Ca_m is Ca in liquid steel measured, ppm.

Because of the higher yield, only pure Ca wires were studied following. As shown in Figure 10, based on Equation

The yields of Si-Ca wires and pure Ca wire

Ca-treatment material	m_a , kg	Ca_m , ppm (on average)	y , %
Si-Ca wire	20	7.24	25.34
Pure Ca wire	20	42.17	46.12

(9) and Equation (10), the amount of pure Ca wires for Ca-treatment of a 210t-ladle could be calculated, with different [Al] and total O. As shown in Figure 10, at some TO , the more [Al] is at the end of RH process, the more pure Ca wires would be needed for Ca-treatment. Therefore, it is necessary to add more pure Ca wires into the liquid silicon steel for Ca-treatment than other steel, because of its higher [Al]. Moreover, Figure 10 also shows that, at some [Al], a increase of pure Ca wires required for Ca-treatment is associated with a increase of total O. For example, in two practical cases, when [Al] is 0.5% and the total O is 30 ppm, and then 50.03 kg of pure Ca wires are required for the Ca-treatment of the heat. However, with the same [Al] and 10 ppm total O, just 41.41 kg of pure Ca wires will be needed .

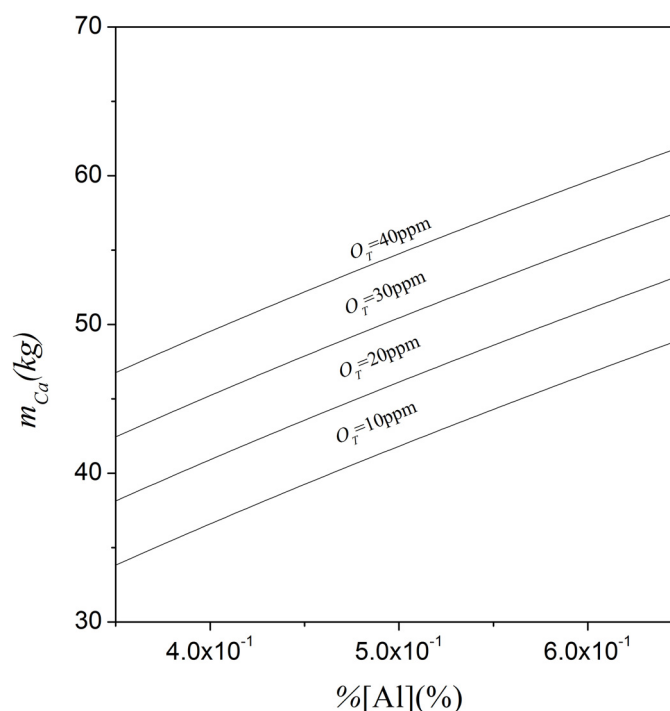


Fig. 10. The relationship between m_{Ca} and $[\text{Al}]$ in liquid steel

5.2. Verification test in steel mill

In order to verify the theoretical analysis mentioned above and prevent ladle nozzle clogging during a CC process of the HNO, some tests were done. The tests were divided into two groups:

- (1) 15 castings of the HNO with Ca-treatment were tested in a month. The amount of pure Ca wires added into the liquid silicon steel for Ca-treatment was on the basis of the

theoretical analysis. The sampling method of the inclusion analysis is also shown in Figure 3, and three samples were taken. Results showed that through the Ca-treatment, most of inclusions were converted into C12A7 and there was a small number of C3A2 inclusions, as shown in Figure 11. Nozzle clogging did not happen in the 15 castings, which was obvious in contrast to 1.5% of the ladle nozzle clogging rate without Ca-treatment.

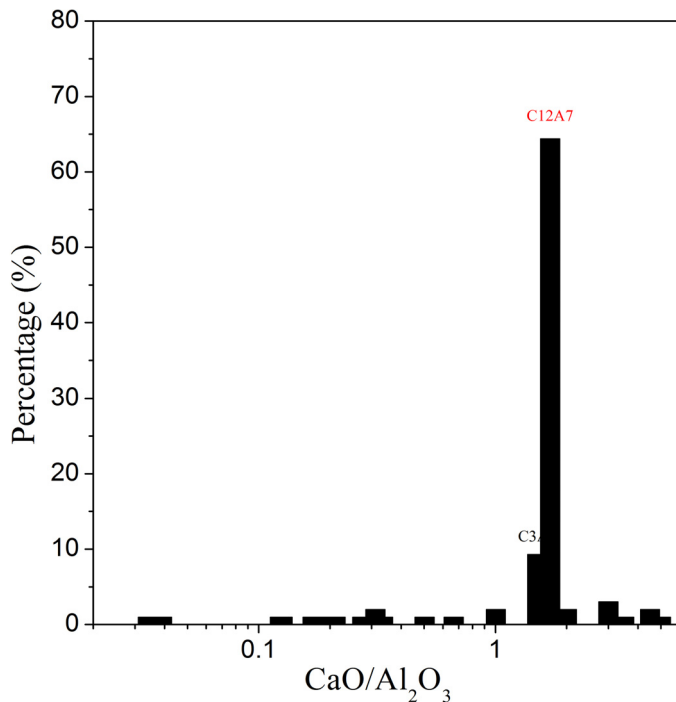


Fig. 11. The percentages of composite inclusions with different CaO/Al₂O₃ applying Ca-treatment with pure Ca wires

(2) [Al] was regulated to be ~0.40% or ~0.55% with basically the same [O] (15 ~ 20 ppm), and the amount of pure Ca wires for Ca-treatment was added based upon the calculation of 0.40% of [Al]. 15 castings with Ca-treatment were respectively tested in three months, in the two [Al]. From the inclusion analysis, it was shown that in the case of [Al] = 0.40%, the percentage of C12A7 in the steel was 66.9%, which was more than 59.2% of [Al] = 0.55%. It indicated that Ca-treatment with more [Al] required more pure Ca wires.

Therefore, the results of the two groups of tests fit the theoretical analysis, and Ca-treatment using pure Ca wires could effectively solve nozzle clogging during a CC process of the HNO.

Moreover, the core loss and the magnetic induction of the HNO with Ca-treatment using pure Ca wires were basically the same as those without the Ca-treatment as shown in Table 5.

6. Conclusions

This paper studied the causes of ladle nozzle clogging during the HNO CC. The theoretical analyses were done. And then a

TABLE 5

The magnetic properties of the HNO with or without Ca-treatment

Process	Magnetic properties (on average)	
	Core loss, W/kg	Magnetic induction, T
With Ca-treatment using pure Ca wires	2.521	1.681
Without Ca-treatment	2.530	1.686

way to prevent the problem was figured out. It is concluded that:

- (1) The bigger diameter of a nozzle or less nozzle clogging can guarantee an enough flow rate for reaching the target casting speed. If the actual value of the percentage of slide gate opening was being smaller than the theoretical one, ladle nozzle clogging has been happening.
- (2) Al₂O₃ and its composite inclusions were the main reason that caused the ladle nozzle clogging during a CC process of the electrical steel.
- (3) Pure Ca wires were yielded better in the liquid HNO than Si-Ca wires. Theoretically higher [Al] or TO will increase the amount of Pure Ca wires for Ca-treatment.
- (4) The results of the verification tests fit the thermodynamic calculation, and Ca-treatment using pure Ca wires could prevent ladle nozzles from clogging during a CC process of the HNO without affecting the magnetic properties.

Acknowledgments

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