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Research Article

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Ladle Nozzle Clogging during casting of Silicon-Steel

Abstract: To figure out the reason causing ladle nozzle clogging during a continuous casting process (or CC for short) for the silicon steel and get a way to solve it, this paper studied the theoretical calculation of flow rates during casting, inclusions around the slide gate where ladle nozzle clogging happened, and Ca-treatment on refining units for producing the silicon steel. 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 analyzing the percentage of a slide gate being opened. Al_2O_3 and its composite inclusions were the main ones which cause the nozzle clogging during the CC process of the silicon steel. Ca-treatment could transform those high melting point inclusions into C12A7 by adding Si-Ca wires and prevent the ladle nozzle clogging of the silicon steel.

Keywords: Ladle Nozzle; Clogging; Non-oriented Silicon Steel; Casting

1 Introduction

Due to nozzle clogging, a casting speed often decreased, and even an entire cast would be canceled in severe cases. Some scientists have been working on the clogging of submerged entry nozzles for years, and they believed that nozzle clogging usually happened due to inclusions aggregating [1–5]. The transformation of inclusions, electroslag remelting process (ESR for short), and ceramic filters were effective methods to reduce the clogging [6–9]. And calcium-treatment for transforming inclusions was thought as a lower cost and a simpler process than the others, and thus there were many studies on it for solving the clogging of submerged entry nozzles [10, 11]. But the researchers thought that some steel with high silicon, such as welding steel, calcium should be not be added into the steel, because it can increase the welding cracks of the steel [12]. That meant that not all steel can use calcium-treatment for solving the clogging, and there has no been a research on ladle nozzle clogging of silicon steel. But there has been being ladle nozzle clogging during CC of silicon steel, which is deoxygenated by using Al. Moreover, silicon steel has unique properties and its processes are more complicated compared to other steel [13–15]. Therefore, it is necessary to study what causes ladle nozzle clogging for casting silicon steel, figure out a effective method to solve the problem, and confirm that the method would not obviously affect the properties of silicon steel. This paper made the theoretical calculation for flow rates that could affect nozzle clogging, analyzed the inclusions causing the ladle nozzle clogging, validated the effects of Ca-treatment on solving ladle nozzle clogging of the silicon steel both theoretically and practically, without a decrease of the magnetic properties.

2 Experimental methods

The paper studied CC of the non-oriented silicon steel, whose chemical composition is shown in Table 1. The steel-making process was BOF(basic oxygen furnace)$\rightarrow$ RH$\rightarrow$ CC.

The dimension of the ladles was 3800 mm (the diameter of the tops)×3200 mm (the diameter of the bottoms)×4006 mm (the height). The side walls and bottoms of the ladles were made of Al_2O_3-MgO-C bricks, and the bricks at the slag-line were MgO-C. The slide gate was made of Al_2O_3-C bricks, and the bricks at the upper nozzles were high-Al_2O_3. The aggregating sand was added for forming better top slag.

A slag thickness before RH was about 80 mm. Pure aluminum particles were added into ladles during RH for deoxidizing.

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Table 1: The chemical composition of the steel after CC (in mass%)

Elements	C	Si	Mn	S	Al	N
mass%	≤ 0.003	0.3-0.4	0.25~0.35	≤ 0.003	0.25~0.35	≤ 0.004

Table 2: The composition of Si-Ca wires

Elements	Si	Ca	C	Al	P	S	Yield/%	
							Si	Ca
wt%	55.0-65.0	≥ 25.0	≤ 1.00	≤ 2.50	≤ 0.045	≤ 0.045	96~98	26~30

In order to change some properties of inclusions and reduce the clogging, we added Si-Ca wires into the liquid steel at the end of an RH process, and a soft bubble-stirring was being applied for 10min. The chemical composition of the Si-Ca wires could be seen in Table 2.

The dimension of the slide-nozzle system and the shroud system under ladles could be seen in Figure 1. And a slide gate was used to control the flow rate of the liquid steel poured from a ladle.

After a casting with 10 heats, where ladle nozzles clogging happened, the samples of the nozzle system and the solid steel in the upper nozzle were taken, as shown in Figure 2. From it, we can see that the edge of a cross section of the solid steel in the upper nozzle was a smooth circle, which indicated there was no obvious clogging in the upper nozzle. However, we found some apparent loose regions with a lot of inclusions and holes around the slide gate, especially at the corner between the upper slide gate and the lower one and close to the wall of the slide gate.

The remaining solid steel in the nozzles was cut into small pieces, and the sampling method is shown in Figure 3. The types, the shapes, the sizes and the distribution of inclusions in the steel samples, which might lead to the ladle nozzle clogging were analyzed by using SEM and EDS.

3 Theoretical calculation of flow rate during casting

A theoretical flow rate of the liquid steel can be calculated by Equation (1), if suppose the slide gate is fully open [16]:

$$Q_m = \rho_l \frac{\pi D^2}{2} \left(\frac{3\alpha g h}{6 + \alpha l} \right)^{\frac{1}{2}} \tag{1}$$

Where Q_m is a flow rate, kg/s. D is the diameter of a nozzle, 0.075 m for the casting. ρ_l is the density of liquid steel, 7000 kg/m³ for this case. α is a constant, 1 for the turbu-
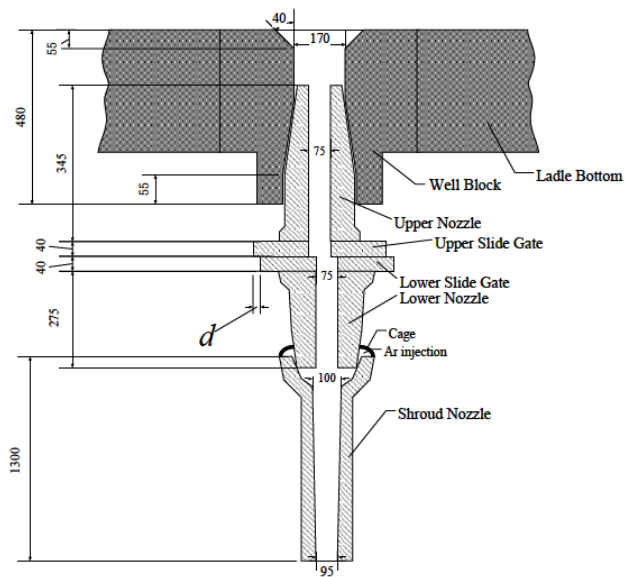
Figure 1: The dimension of the slide-nozzle system and the shroud system

lent flow studied. g is the acceleration of gravity. h is the height of the liquid level of rest steel from the bottom of a ladle, m. l is a friction loss factor, 0.5 for the case.

A flow rate through the nozzle (Q_{mc}) can be expressed by Equation (2).

$$Q_{mc} = w \cdot t \cdot \rho_s \frac{s_c}{30} \tag{2}$$

where w and t are respectively the width and the thickness of a slab, 1.3 m and 0.23 m for the study. ρ_s is the density of solid steel, 7797 kg/m³ for the case. s_c is a casting speed for two strands, 1.1m/min for the target of this case. Then, based on Equation (2), the Q_{mc} should be 85.48 kg/s, *i.e.* 5.13 t/min for reaching the target casting speed in the case of the two strands of the CC.

As shown in Figure 4 based on Equation (1) and Equation (2), associated with a decrease of the height of a liquid level, the flow rate deceases. And if a height deceases from 4m to 1.5m, there would be a about 50 percent reduction
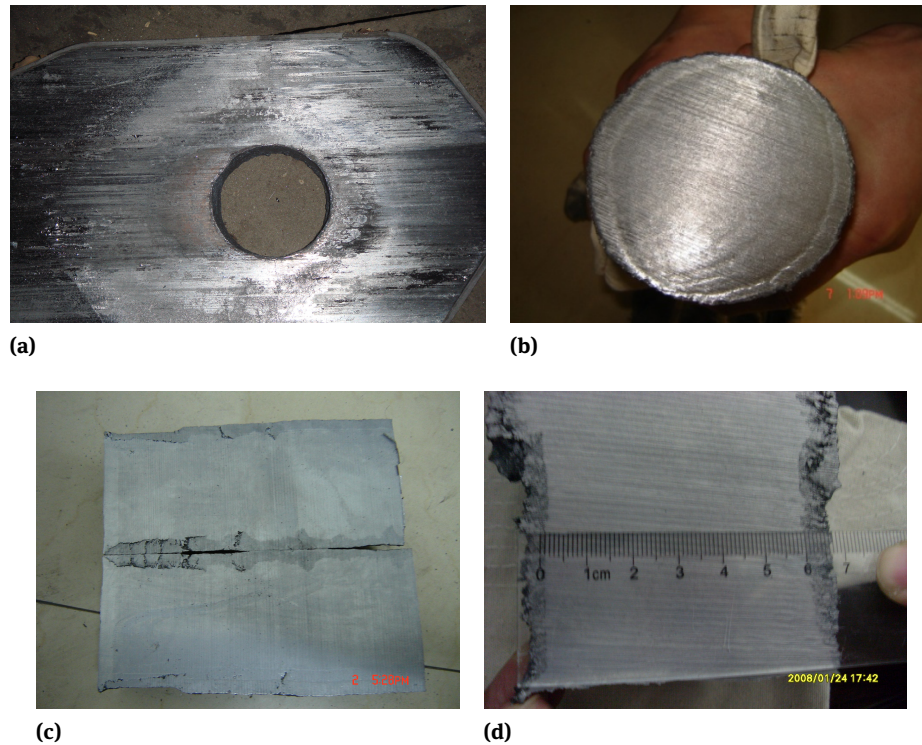
(a)

(b)

(c)

(d)

Figure 2: The samples after casting: (a) the used slide gate, (b) a cross section of the solid steel in the upper nozzle, (c) longitudinal sections of the solid steel, (d) a part of Figure 2(c) around the slide gate.
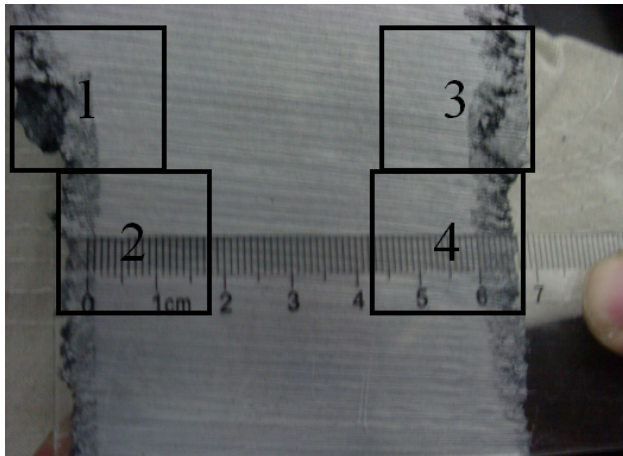

Figure 3: The sampling method (the samples cut from the balck boxs)

Figure 4: The relationship between Q_m/S_c and h during casting

in the flow rate. We can also see that the bigger diameter of a nozzle means a higher flow rate and casting speed. If a nozzle diameter is 90 mm, even though a height is obviously below 0.5 m, the casting speed can reach the target of 1.1m/min. And if a nozzle diameter is 60 mm, even though a height is 1m (two times of the height above), the casting speed will not reach the target (only 0.98 m/min, *i.e.* 84.14
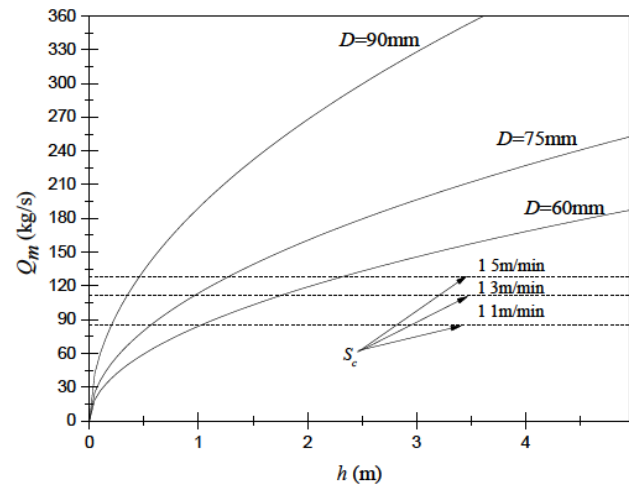
kg/s). It is indicates that the bigger diameter of a nozzle could effectively generate an enough flow rate for CC.

The theoretical flow rate controlled by an percentage of a slide gate opened, Q_{mc} in kg/s, can be calculated by the following Equation:
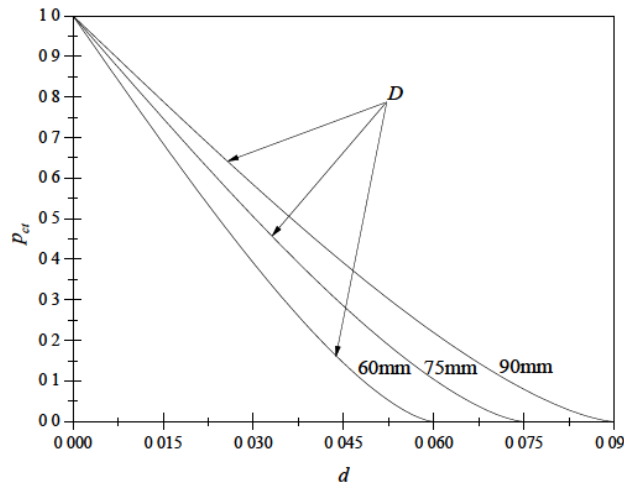
$$Q_{mc} = p_{ct} \cdot Q_m \qquad (3)$$

Figure 5: The relationship between p_{ct} and d during casting

Figure 6: The Relationship among p_{ct}, S_v, D and h

where p_{ct} is the percentage of a slide gate opened, which can be calculated by Equation (4)

$$p_{ct} = \frac{a}{\pi D^2 / 4} = \frac{2\left(\arccos\frac{d}{D} - \frac{d}{D^2}(D^2 - d^2)^{\frac{1}{2}}\right)}{\pi} \quad (4)$$

where a is the area of a slide gate opened, m^2. d is a distance that a lower slide gate moves, m, also as shown in Figure 1. Based on Equation (4), as shown in Figure 5, we could easily see 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.

Based on Equation (1), Equation (2) and Equation (3), we could get:

$$p_{ct} = \frac{w \cdot t}{15\pi D^2} \cdot \frac{\rho_s}{\rho_l} \cdot s_c \left(\frac{3\alpha gh}{6 + \alpha l}\right)^{-\frac{1}{2}} \quad (5)$$

Plug the values of the variables for this study, as shown above, into Equation (5), and it can be reduced to this:

$$p_{ct} = 3.32 \times 10^{-3} \cdot \frac{s_c h^{-\frac{1}{2}}}{D^2} \quad (6)$$

Based on Equation (6), the relationship among p_{ct}, S_v, D and h could be shown in Figure 6. If the diameter of a nozzle is 95 mm and the liquid level of rest steel is 4m (at the beginning of a casting), a slide gate opened of 22.54% can lead to the target casting speed of 1.1 m/min. As the liquid level of rest steel decreases to 1m, the slide gate must move to open to 45.09% (two times of the beginning) for reaching the target casting speed. If the nozzle is clogged to a smaller diameter such as 60 mm and the liquid level of
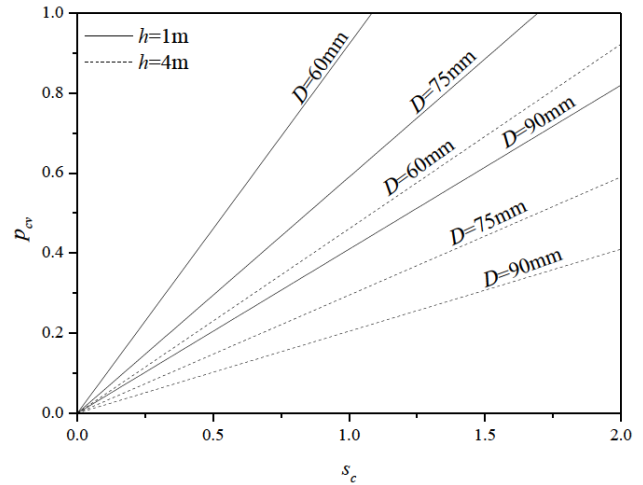
rest steel is 1m, almost a fully opened slide gate can meet the demand of the casting speed of 1.1 m/min. However, as the liquid level of rest steel decreases to 0.5 m, even the slide gate of 100% can not generate the target speed. And at the same time, in order to keep a steady liquid steel level in the tundish, the casting speed has to decrease. From Figure 6, for a fixed slide gate diameter, we could also figure out the appropriate p_{ct} that can maintain different casting speeds. Such as 75 mm in this case of a casting speed of 1.1 m/min or 1.5 m/min, the p_{ct} at least is supposed to be 32.46% or 44.27% maintaining sufficient liquid steel in the tundish. It can be indicated that if the actual value of p_{ct} is higher than the theoretical one of p_{ct}, then clogging in the ladle nozzle have been happening.

4 Inclusions analysis

As shown in Figure 7, most of inclusions were the ones containing Al_2O_3, and distributed alone or like a chain. We also observed a small number of pure Al_2O_3 inclusions and CaO inclusions. The shapes of the composite inclusions were irregular, and their sizes were big, even as large as a few centimeters. We believe that those inclusions were generated from deoxidation and adding the Al content (for meeting performance requirements of the silicon steel) by using Al-alloy, and from the reaction between Al_2O_3 and slag/furnace lining(Al_2O_3-MgO-C bricks or MgO-C bricks shown above). We also notice that there were some inclusions with a high contents of FeO, even as high as 50%. It is could be explained that: ① There was severe air absorbed consuming local [Al], and then the O_2 from the air reacted with liquid Fe to form [FeO] ($2Fe(l)+O_2 = 2(FeO)$), during the
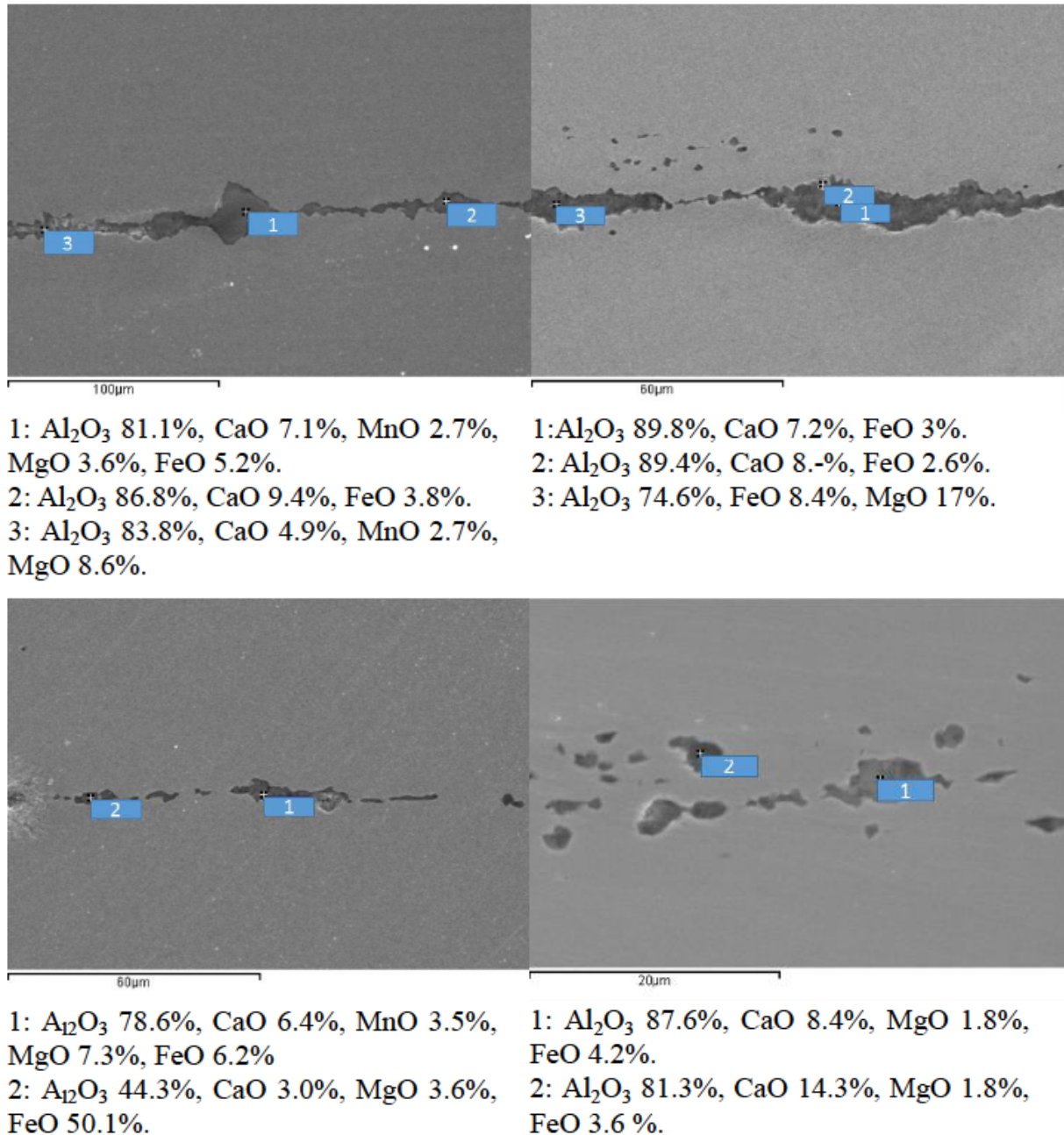
1: Al_2O_3 81.1%, CaO 7.1%, MnO 2.7%, MgO 3.6%, FeO 5.2%.
2: Al_2O_3 86.8%, CaO 9.4%, FeO 3.8%.
3: Al_2O_3 83.8%, CaO 4.9%, MnO 2.7%, MgO 8.6%.

1: Al_2O_3 89.8%, CaO 7.2%, FeO 3%.
2: Al_2O_3 89.4%, CaO 8.-%, FeO 2.6%.
3: Al_2O_3 74.6%, FeO 8.4%, MgO 17%.

1: $A_{l2}O_3$ 78.6%, CaO 6.4%, MnO 3.5%, MgO 7.3%, FeO 6.2%
2: $A_{l2}O_3$ 44.3%, CaO 3.0%, MgO 3.6%, FeO 50.1%.

1: Al_2O_3 87.6%, CaO 8.4%, MgO 1.8%, FeO 4.2%.
2: Al_2O_3 81.3%, CaO 14.3%, MgO 1.8%, FeO 3.6 %.

Figure 7: Inclusions in steel around the slide gate

casting. ② EDS might detect 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 in the inclusions occur due to the first reason. For reducing the error caused by the second reason, we ignored the FeO content of the inclusions, and then the inclusions mainly contained >60% Al_2O_3, 20~30% MgO+CaO and other components.

Only calculating Al_2O_3, CaO and MgO, the content and the state (liquid or solid) of each of the inclusions are shown in Figure 8. It could be indicated that almost all the inclusions (96%, 65 of 68) were solid at the casting temperature (1530°C). The melting points of other three liquid inclusions at the casting temperature were between 1300°C and 1530°C, with CaO of 60%~70% in this three-phases diagram. Most of those inclusions with a low melting point would flow away with liquid steel, and not be the reason causing the nozzle clogging.

The molecular ratios of the CaO/Al_2O_3 are shown in Figure 9. An inclusion based on CaO-Al_2O_3 would become
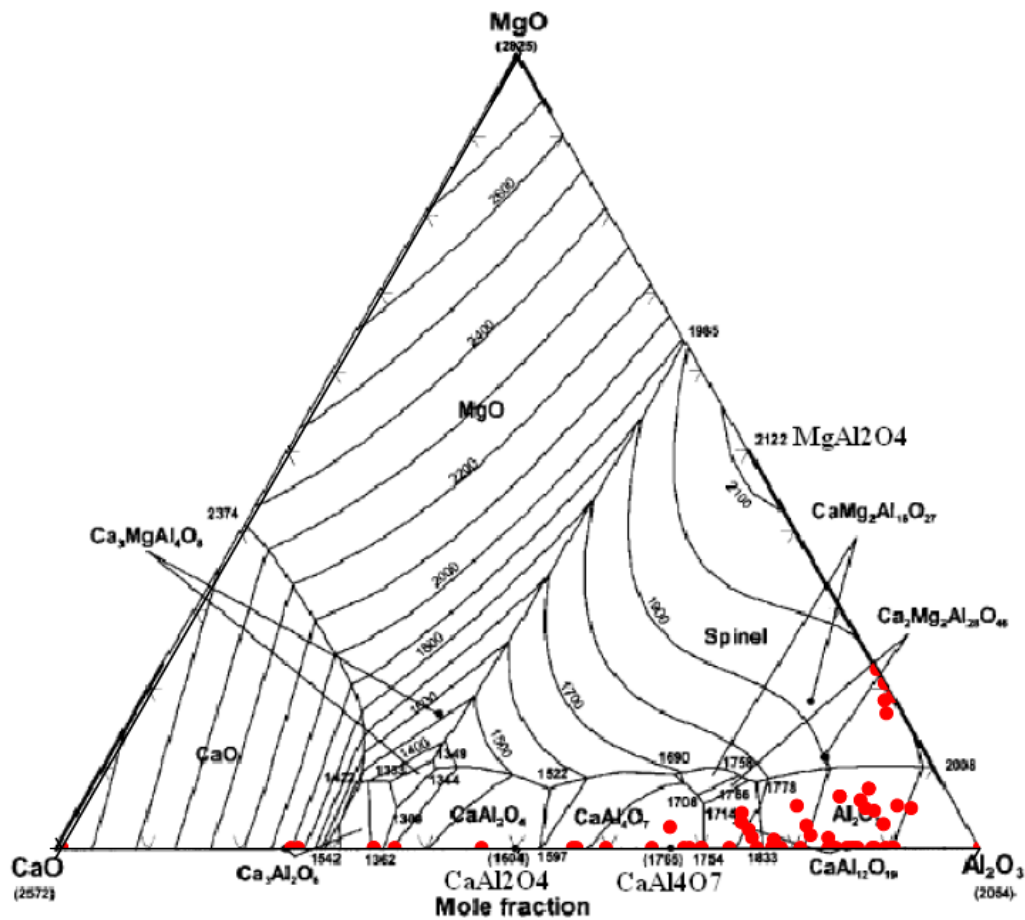
Figure 8: The inclusions in the steel in the Al_2O_3-CaO-MgO diagram with the isograms of the melting points [17]

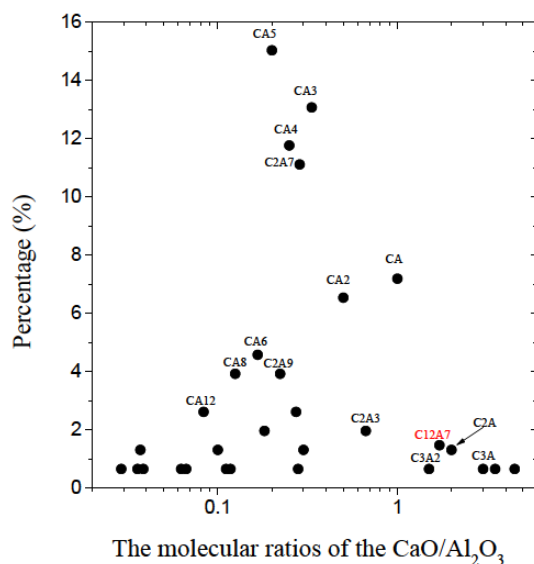**Figure 9:** The percentages of the composite inclusions with the different molecular ratios of CaO-Al_2O_3

liquid during a casting of steel with its molecular ratio being 1.7 or 3 [18]. However, from the figure, it could be seen that most of the inclusions are not 12CaO·7Al_2O_3 (or C12A7 for short, whose melting point is the lowest in the slag) or 3CaO·Al_2O_3 (or C3A for short). And .Therefore, we could use Ca-treatment to transform these inclusions with the high melting-points into those with the lowest melting point of 12CaO·7Al_2O_3. And improve the nozzle clogging and the final product quality of the silicon steel.

5 Ca-treatment for preventing silicon steel from nozzle clogging

5.1 Thermodynamic calculation of Ca-treatment

Ca-treatment is a method that could modify inclusions in steel by adding Si-Ca wires or pure Ca wires and form low melting point inclusions of C12A7 or C3A to prevent nozzle

clogging, at a refining unit. In this study, we only dealt with C12A7 (because of the lowest melting point) by using Ca-treatment. C12A7 formed by the reaction of Ca plus Al_2O_3 can be shown in Equation (7) [19]:

$$12[Ca] + 11(Al_2O_3) = (CaO)_{12}(Al_2O_3)_7 + 8[Al] \quad (7)$$
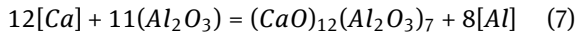
When the reaction is at equilibrium, the relationship between [Al] and [Ca] would be $w[Ca]=1.26\times10^{-2}w[Al]^{2/3}$, and the relationship between [Al] and [O] would be $w[O]=1.74\times10^{-5}w[Al]^{-2/3}$, according to the thermodynamic data and the stoichiometric coefficients [20, 21]. It is indicated that once $w[Al]$ is measured before Ca-treatment, corresponding $w[Ca]$ for forming C12A7 can be determined. And too much or too little Ca would generate other high melting point inclusions, and even sufficient Ca may react with [S] in liquid steel.

Suppose that all oxides reacted with [Ca] is Al_2O_3, and then the rate of Ca in liquid steel, for the reaction of Equation (7) (Ca_{Re} in ppm) can be calculated the following Equation:

$$Ca_{Re} = \frac{4Ar_{Ca}}{11Ar_O}(O_T - [O]) \quad (8)$$
$$= 0.909\left(O_T - 1.74 \times 10^{-1}w[Al]^{-\frac{2}{3}}\right)$$

Where Ar_{Ca} and M_O are respectively the atomic mass of Ca and O. O_T is total oxygen, which includes oxygen in oxides and dissolved oxygen, in steel, ppm. [O] is dissolved oxygen, ppm. And then total Ca in steel (in ppm) can be divided into two parts we refer to as Ca_{Re} and Ca at equilibrium (in ppm). Therefore, Si-Ca wires used for Ca-treatment per heat (M_{Si-Ca} in kg) can be calculated by the following Equation:

$$M_{SiCa} = \frac{M_s}{a \cdot y} \cdot \left[1.26 \times 10^{-4}w[Al]^{\frac{2}{3}} \quad (9)$$
$$+9.09 \times 10^{-7}\left(O_T - 0.174w[Al]^{-\frac{2}{3}}\right)\right]$$

Where M_s is the capacity of a ladle, 2.1×10^5 kg for the current study. a is the mass fraction of Ca in a Si-Ca wire, 30% for the current study. y is the yield of the Ca of a Si-Ca wire in steel, 28% for the current study. Furthermore, based on Equation (9), the total length of Si-Ca wires for Ca-treatment per heat (L_{Si-Ca}) can be calculated by:

$$L_{SiCa} = \frac{4}{\pi D_{Si-Ca}^2} \cdot \frac{M_{Si-Ca}}{w[Si]\rho_{Si} + w[Ca]\rho_{Ca}} \quad (10)$$

Where D_{Si-Ca} is the diameter of a Si-Ca wire, 0.013m for the current study. ρ_{Si} is the density of Si, 2330 kg/m^3. ρ_{Ca} is the density of Ca, 1550 kg/m^3.

As shown in Figure 10 and Figure 11, we could easily get the amount of Si-Ca wires for Ca-treatment of a 210t ladle, with different dissolved Al and total O. From Figure 10,
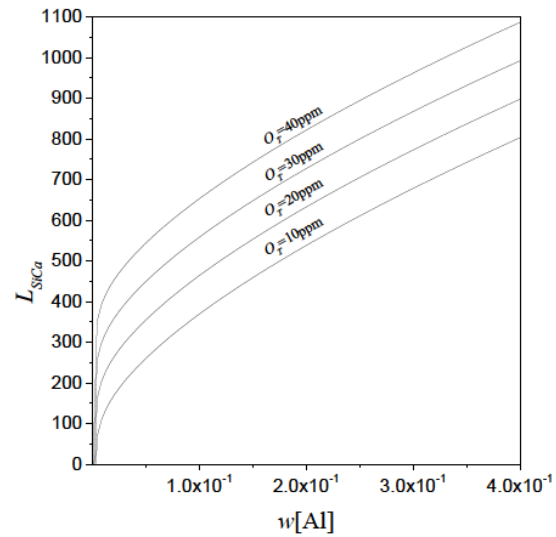

Figure 10: The relationship between L_{Si-Ca} and $w[Al]$ in liquid silicon steel
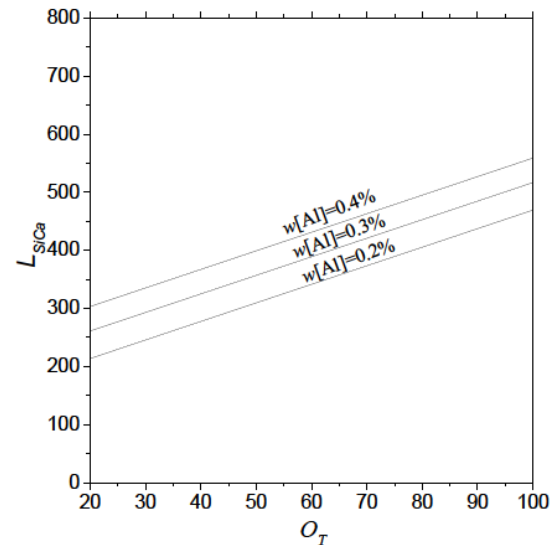

Figure 11: The relationship between L_{Si-Ca} and total oxygen in liquid silicon steel

it can be indicated that under a O_T, the more dissolved Al is in liquid silicon steel at the end of RH process, the more Si-Ca wires would be needed for Ca-treatment. Figure 11 shows that under a dissolved Al, associated with a increase of total O, Si-Ca wires required raise. For example, in two practical cases, when the dissolved Al is 0.3% and the total O is 30 ppm, and then Si-Ca wires of 867 m would be required for the Ca-treatment of the heat. However, with the same dissolved Al and the total O of 10 ppm, we just need 678 m. Furthermore, it is necessary to add more Si-Ca wires into liquid silicon steel for Ca-treatment than other steel, because of its higher [Al].

Table 3: The magnetic properties of the silicon steel with or without Ca-treatment

| Process	Magnetic properties (on average)	
	Core loss, W/Kg	Magnetic induction, T
With Ca-treatment	5.391	1.749
Without Ca-treatment	5.406	1.758

5.2 Verification tests in steel plant

In order to verify the theoretical analysis mentioned above and prevent a nozzle from clogging during a CC process of the silicon steel, a number of tests were done. These tests were divided into two groups:

1. The quantity of Si-Ca wires added into the liquid silicon steel for a heat was on the basis of the theoretical analysis. And 15 castings with Ca-treatment were tested in a month. The sampling method of the inclusion analysis was the same as what is shown in Figure 3, and three samples were drawn. Through the Ca-treatment, most of inclusions were transformed into C12A7 and there was a small number of C3A2, as shown in Figure 12. And nozzle clogging did not happen in the 15 castings, whose effects were obvious in contrast to the nozzle clogging rate of 1.5% without Ca-treatment.

2. Al was adjusted to ~0.25% or ~0.35% with basically the same [O] (15~20ppm), and the quantity of Si-Ca wires for a heat was added by the calculation of [Al] of 0.25%. Ca-treatment with the two [Al] were respectively tested 15 castings in two months. The results of the inclusion analysis showed that in the case of [Al]=0.25%, the percentage of C12A7 in the steel was 68.5%, which is more than 53.5% of [Al]=0.35%. It is indicated that Ca-treatment with more [Al] needs more Si-Ca wires.

In conclusion, the results of the two groups of tests fit the theoretical analysis, and Ca-treatment can solve nozzle clogging during a CC process of the silicon steel.

Moreover, the core loss and the magnetic induction of the silicon steel slightly lowered by using Ca-treatment as shown in Table 3. More [Si] might be a reason leading to the little difference, and we will do further research to study the relationship between Ca-treatment and the magnetic properties.
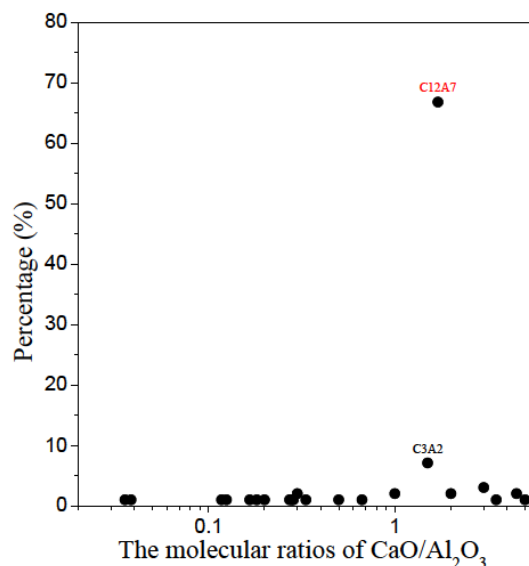
Figure 12: The percentages of composite inclusions with different CaO: Al_2O_3 applying Ca-treatment

6 Conclusions

This paper studied the causes of nozzle clogging during a CC process of the silicon steel, and theoretical analyses were done. Furthermore, we figured out a way to solve this problem. We concluded that:

1. The bigger diameter of a nozzle or less nozzle clogging could effectively generate an enough flow rate for a CC process and maintain the target casting speed. We can predict if nozzle clogging is happening by comparing the actual value and the theoretical one of the percentage of a slide gate opened

2. The main inclusions which caused the nozzle clogging during a CC process of the silicon steel were Al_2O_3 and its composite inclusions.

3. Ca-treatment can be a method that transform inclusions into C12A7 by adding Si-Ca wires and prevent nozzle clogging of the silicon steel theoretically. And the amount of Si-Ca wires for Ca-treatment of the silicon steel, with different dissolved Al and total O can be calculated.

4. The results of the verification tests fit the theoretical analysis, and Ca-treatment can prevent the nozzles from clogging during a CC process of the silicon steel.

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