Study on heat transfer mechanism of pure calcium cored wire in molten steel by feeding rate

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In order to descript heat transfer mechanism of pure calcium cored wire in molten steel accurately and comprehensively, the temperature changes of the pure calcium cored wire fed into the molten steel at different feeding rate were studied using heat transfer finite element model of pure calcium cored wire in molten steel. Experimental results show when the molten steel temperature is 1570 ℃, and the feeding rate is 1.50m/s-5.00m/s, the time required for the pure calcium core to reach the melting point is 1.19s-1.43s, and the time to reach the boiling point is 2.75s-3.36s; When the temperature of the calcium core reaches the boiling point of 1484 ℃, the steel sheet of the pure calcium cored is 1496 ~1498 ℃, and the steel sheet is in the state of non-melting. Through numerical simulation and industrial test, the best feeding rate is 1.75m/s, and the yield of calcium is 26.1%, which provides technical guidance for the research and development of calcium treatment process.

KEYWORDS: PURE CALCIUM CORED WIRE – FEEDING RATE – MELTING POINT – BOILING POINT – CALCIUM TREATMENT PROCESS

INTRODUCTION

In the process of molten steel refining, Calcium silicon cored wire are adopted in most of the plants. The core of the calcium silicon wire is filled with powdered calcium silicate powder, and the exterior is wrapped with steel sheet. Silicon calcium powder has the drawback of uneven and unstable. Moreover, the granular material has large specific surface area and large gas gap. The calcium in it is easily oxidized during storage and transportation, so that calcium is wasted [1-3] in vain, resulting in low calcium yield. In addition, the calcium silicon cored wire also adds more silicon in the molten steel, which makes it difficult to control the silicon content produced in the low silicon content steel grade. Besides, during the use process, because of the low strength of calcium silicon cored wire, it is easy to slip and run away when feeding wire, which brings adverse effects to the precise control of calcium content and stable continuous production. Pure calcium cored wire with external steel sheet and internal high density solid cored pure calcium rod high-pressure pulled out, being not slippery, without deviation while wire feeding, can feed the calcium into deep position of molten steel, without adding silicon, or other impurities, so as the raising of varieties of steel smelting requirements, in order to improve the effect of calcium treatment, and increase the purity of molten steel[4,5], the study of pure calcium cored wire replacement calcium silicon cored wire is started. Calcium is a flammable and readily oxidizable metal, which can not be observed at normal temperature. After the feeding of molten steel, the melting and gasification process of pure calcium cored wire cannot be observed. The change of pure calcium cored wire temperature and the melting and gasification behavior after entering molten steel cannot be directly measured. Therefore, the finite element method is used to simulate the melting and gasification mechanism of pure calcium cored wire feeding into molten steel at different feed speed, which provides a theoretical basis for the specification model of pure calcium cored wire and the wire feeding process optimization.

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Numerical model establishment

Selection of model parameters

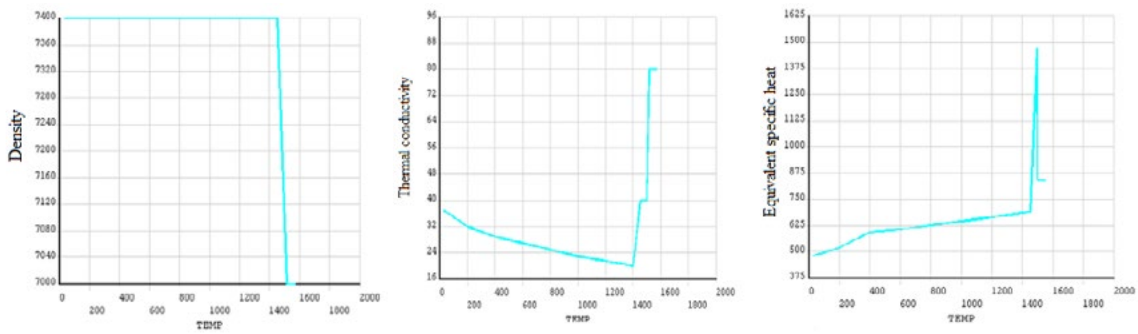
The diameter of the pure calcium cored wire is 8.82mm, the diameter of the pure calcium core is 7.7mm, and the thickness of the steel sheet is 0.56mm.

Calcium content of the pure calcium cored wire is more than 95%, core weight: sheet weight =3:7

The physical parameters of the metal Ca are shown in Table 1, and the physical properties of steel are shown in Fig. 1.

Tab. 1 – Physical properties of metal calcium

melting point (℃)	boiling point (℃)	atomic quantity	density (kg/m^3)	specific heat (J/Kg.K)	thermal conductibity (W/m.K)	calcium core weight (g/m)
839	1484	40.08	1550	632	201	67



(a) (b) (c)

(a) Density (b)Thermal conductivity (c)Equivalent specific heat

Fig. 1 – Physical properties of steel

(1) The initial condition and boundary condition of the model

Set 1570℃ in refining end of low carbon steel as the initial temperature of the molten steel, room temperature of 20℃ as pure calcium cored wire initial temperature, the heat transfer between molten steel and pure calcium cored wire as the third boundary condition, pure calcium cored wire enter into the molten steel at a certain speed that is strong for the convective heat transfer boundary condition. The convection heat transfer coefficient between the molten steel and the pure calcium cored wire is calculated by Eq.1.

$$h = A \cdot \left(\frac{D \cdot v \cdot \rho}{\mu}\right)^{0.8} \cdot \left(\frac{C \cdot \mu}{\lambda}\right)^{0.4} \cdot \left(\frac{\lambda}{D}\right) \quad [1]$$

where

A–Comprehensive heat transfer coefficient, 3.6~6.8×10^{-3},take 4.17×10-3;

D–Pure calcium cored wire diameter, 0.882×10^{-2}m;

V–the speed of pure calcium cored wire entering into molten steel, 1.50~5.00m·s-1;

P–Steel density, 7×10^{3}Kg·m^{-3};

μ–Dynamic viscosity of molten steel, 5.5×10-3Kg·s·m^{-2};

C–Specific heat of molten steel, 842 J·Kg^{-1}· -1.

λ–Thermal conductivity of molten steel,20~37 W·m^{-1}· -1.

The convective heat transfer coefficient of its corresponding molten steel and pure calcium cored wire is shown in Table 2.

Tab. 2 – Convective heat transfer coefficient of molten steel and pure calcium cored wire at different feeding rate.

Feeding rate, m/s	1.50	1.75	2.00	3.00	4.00	5.00
Convective heat transfer coefficienth, W/m2.˚C (×103)	12.67	14.33	15.96	22.06	27.77	33.20

In order to simplify the calculation, the steel shell condensed on the outer surface of pure calcium cored wire when the pure calcium cored wire just enters the molten steel is not considered. While the calcium core is simulated, when the calcium core reaches or exceeds the boiling point, it is still not treated with gasification for convenience of calculation.
(2)The establishment of the model
Since pure calcium cored wire length is far greater than the cross-sectional size, heat transfer is basically in the two-dimensional space, the heat transfer along the length direction of the transfer wire is negligible. So the 2D finite element method is adopted in this model pure calcium cored wire model is set by two dimensional modeling and divided into a finite element mesh, model element number is 2060, the number of nodes is 2109, the finite element model of heat transfer wire as shown in Fig. 2.

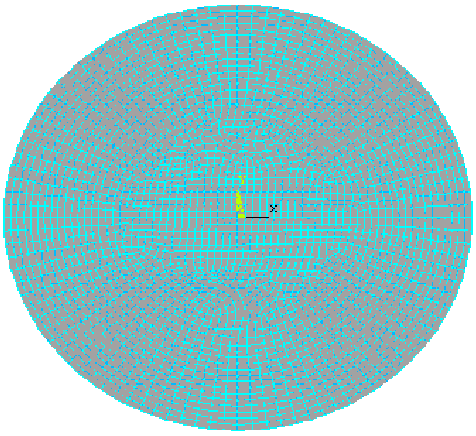


Fig. 2 – The finite element model of heat transfer of pure calcium cored wire

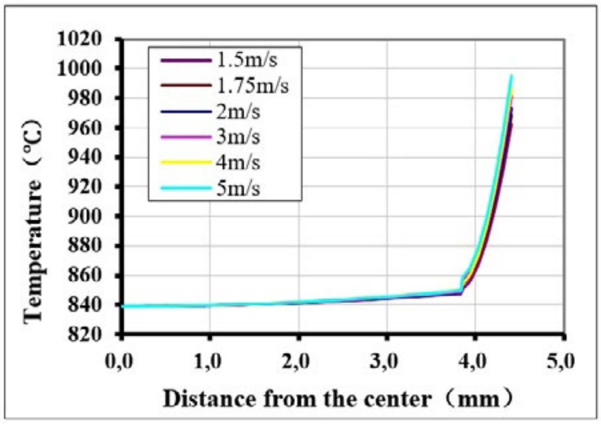
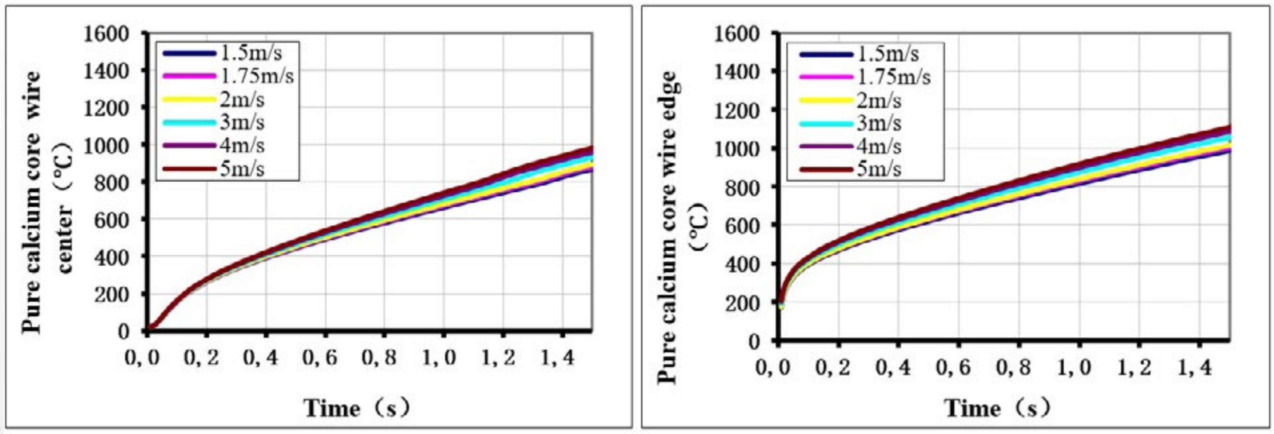


Fig. 3 – Temperature distribution of cross section of pure calcium cored wire at different feeding rate

Based on Fig. 2, combined the diameter of the pure calcium core is 7.7mm, so the calcium core is within 3.85mm of the center, and from 3.85mm to 4.41mm part is the steel sheet.

INFLUENCE OF MELTING OF CALCIUM CORE AT DIFFERENT FEEDING RATE

First, the temperature of the cross section of the pure calcium cored wire is calculated when the pure calcium cored wire is inserted into the molten steel at different feeding rate to reach the melting temperature. The results are shown in Fig. 3.
From Fig. 3, it can be seen that the temperature difference inside the calcium core (0-3.85mm,the same below) is very small at different feeding rate, and the temperature of the steel sheet (when the distance is greater than 3.85mm, the same below) increases with the increase of feeding rate. This is because the thermal conductivity of calcium core is much larger than the thermal conductivity of steel sheet. The steel sheet becomes a restrictive part of heat transfer, so the heating rate is different, and the heating rate of calcium core with relatively fast heat conduction speed is not very different. It is worth noting that there is an obvious temperature gradient due to the contact heat transfer between two substances at the junction surface of 3.85mm calcium core and steel sheet, and the temperature gradient increases with the increase of wire feeding rate.
Because the outer layer is steel sheet and its melting point is high, when the pure calcium core reaches the melting temperature of 839˚C, the steel sheet is far below its melting temperature, that is, it is still solid.
In order to obtain the time required for the melting point of the calcium core at different feeding rate, the temperature changes of the center and edge of the pure calcium cored wire with time are analyzed, as shown in Fig. 4.



(a) Pure calcium cored wire center (b) Pure calcium cored wire edge

Fig. 4 – The temperature change of pure calcium cored wire with time at different feeding rate

From Fig. 4, it is known that the temperature at both the center and the edge of pure calcium cored wire increases with time, and the heating rate decreases with the increase of time. The higher the feeding rate is, the higher the temperature of the center and the edge of the pure calcium cored wire is.

From Fig. 4 (a), it is known that when the feed speed is 1.5m/s, 1.75m/s, 2m/s, 3m/s, 4m/s and 5m/s, the time of pure calcium core temperature rises to the melting point, that is, the melting time of pure calcium cored wire core is 1.43s, 1.40s, 1.38s, 1.29s, 1.38s, 1.29s, 1.23s and 1.19s.

INFLUENCE ON CALCIUM CORE GASIFICATION AT DIFFERENT FEEDING RATE

When the calcium core reaches gasification temperature, The existence state of steel sheet in the outer layer of pure calcium cored wire has a great influence on the pure calcium cored wire, In the case of liquid, the calcium core can break through the liquid steel sheet and react with the molten steel directly. If the steel sheet is still solid, the core should be ejected from the end to react with the molten steel. Therefore, in order to get the existence state of the steel sheet when the calcium core reaches the gasification temperature, the temperature change of the cross section of pure calcium cored wire at different feeding rate when it reaches the gasification temperature is calculated, and the results are shown in Fig. 5 to 9.

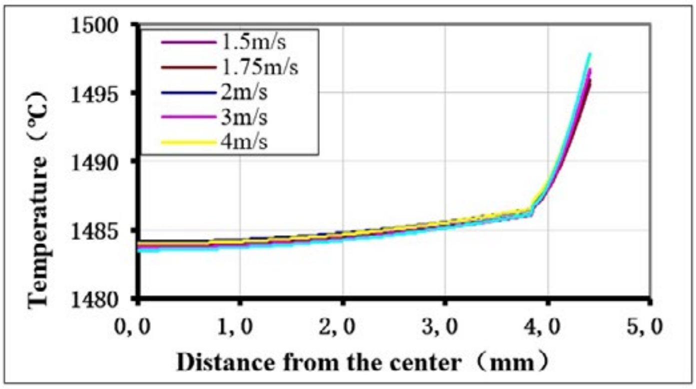
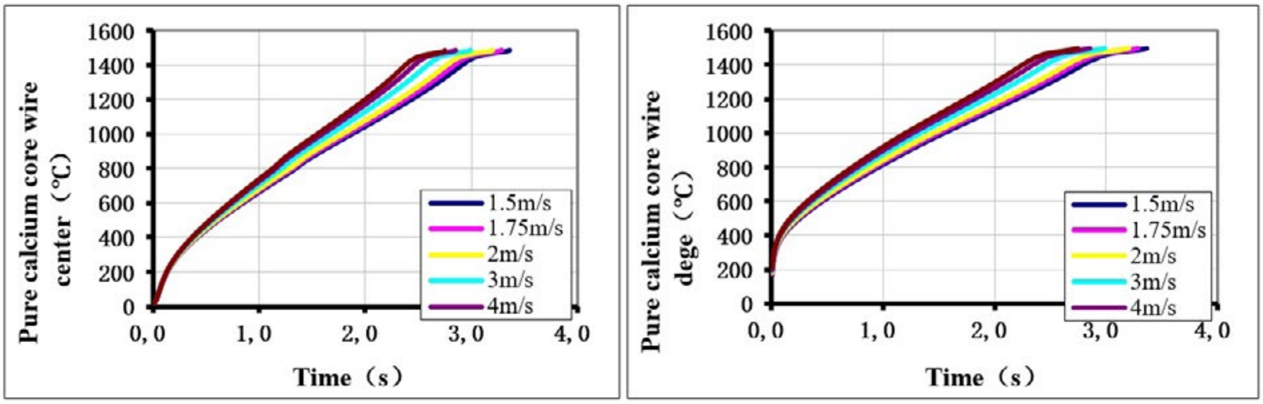


Fig. 5 – Temperature distribution of cross section of pure calcium cored wire at different feeding rate

Fig. 5 shows the temperature distribution of cross section of pure calcium cored wire at different feeding rate. It is known that the temperature change is the same as that of the Fig3, but the temperature difference between the calcium core and the steel sheet is smaller when the calcium core reaches the gasification temperature. When the feeding rate is 1.5m/s, 1.75m/s, 2m/s, 3m/s, 4m/s and 5m/s, the temperature difference between the core edge and the center is 11.7°C, 12.1°C, 12.3°C, 13°C, 13.7°C, 14.3°C, respectively.

The temperature change of the center and edge of the pure calcium cored wire at different feeding rate is shown in Fig. 6



(a) Pure calcium cored wire center (b) Pure calcium cored wire edge

Fig. 6 – The change of pure calcium cored wire temperature with time at different feeding rate

From Fig. 6, we know that the temperature at both the edge and center of the pure calcium cored wire increase with time, while the heating rate decreases with time. The higher the feeding rate is, the higher the temperature of the center and the edge of the pure calcium cored wire is.

The center temperature of the pure calcium cored wire rises to the boiling point at 1484°C, that is, the gasification temperature, is taken as the standard. It can be get that when the wire feeding rate are 1.5m/s, 1.75m/s, 2m/s, 3m/s, 4m/s, 5m/s, The time of the pure calcium cored wire to reach the gasification temperature correspondingly are: 3.36s, 3.28s, 3.20s, 2.99s, 2.85s, 2.75s.

The steel of the outer layer of pure calcium cored wire (the steel sheet) is SPCC. According to its chemical composition, the solidus temperature is 1474°C, and the liquidus temperature is 1524°C. In the mushy zone, the dividing wire of the solid fraction fs is 0.7, and the corresponding temperature is 1509°C. When the solid fraction fs is less than 0.7, it is considered that the mixed area of solid liquid phase is pure liquid zone, that is, the melting temperature of outer skin is 1509°C. According to Fig. 6, when the calcium core temperature rises to 1484°C, the temperature of steel sheet is 1496°C~1498°C, so it doesn't melt.

INDUSTRIAL TEST VERIFICATION OF PURE CALCIUM CORED WIRE MELTING MECHANISM

In order to verify the calculation results of the melting mechanism of pure calcium cored wire, an industrial trial was carried out. The appearance of pure calcium cored wire pulled out from molten steel in different time is shown in Fig. 7. The appearance of the pure calcium cored wire is shown in Fig. 8.

(a) 2.53s (b) 2.53s (c) 2.93s (d) 3.20s

Fig. 7 – The appearance of pure calcium cored wire pulled out from molten steel in different time

Fig. 8 – Pure calcium cored wire melting appearance

From Fig. 7, based on the analysis of residual pure calcium cored wire end, when the pure calcium cored wire enters the molten steel, firstly, the pure calcium cored wire end is quickly heated to the liquid. At this time, the temperature of the steel sheet did not reach the melting point. Therefore, the calcium core was in a liquid state in the tube formed by the steel sheet, and then dropped off after leaving the molten steel and had strong chemical reaction with oxygen in the air, as shown in Fig. 7 (a) and (b). If the time of the pure calcium cored wire in the molten steel is prolonged, the calcium core end is continuously heated in the molten steel and turns into a gaseous state. The gaseous calcium will be ejected from the pure calcium cored wire end to form calcium vapor and directly react with oxygen in the air, as shown in Fig. 7 (c). The calcium vapor floats in the molten steel and partially melted in the molten steel during the floatation. The non melting part is lost in the air, and the gaseous calcium will accelerate the melting of the steel sheet during the ejection process. When the critical time is exceeded, the calcium core will be vaporized and the steel sheet will be melted completely, that is, the pure calcium cored wire is melted into the molten steel, as shown in Fig. 7 (d).

In Fig. 8, the main component of the white substance on the end of the pure calcium cored wire is calcium compounds, the pure calcium cored wire is wrapped with slag in the other parts except the end. After removing the slag from the pure calcium cored wire, the surface is covered with a layer of steel shell. It is known that when the pure calcium cored wire is inserted into the molten steel, the molten steel contacted with the pure calcium cored wire is cooled and adhered to the pure calcium cored wire. This act prevents the pure calcium cored wire except the end from being molten or even vaporized firstly, In other words, the melting and gasification of the pure calcium cored wire start from the end and gradually move back. This helps to insert the pure calcium cored wire into the molten steel deeper and increases the yield of calcium.

FEEDING RATE CONTROL

The feeding rate of the pure calcium cored wire should have an appropriate value. If the feeding rate is too high, the calcium in the ladle will be too concentrated, After the pure calcium cored wire is completely melted, a large amount of calcium vapor is produced locally, forming a large number of "bubbles". In the process of floatation, a large number of "bubbles" can not be absorbed by molten steel and a large amount of molten steel escapes, resulting in seething and splashing of molten steel, and reducing the yield of calcium. If the feeding rate is too slow and the time of calcium gasification is prolonged, the pure calcium cored wire will be centralized and vaporized at the bottom, which will also cause the above situation and reduce the yield of calcium.

The depth of the molten steel is calculated by 3m, and the pure calcium cored wire is not vertically downward after entering the molten steel, but it will spiral or bend down. So the path of the pure calcium cored wire reached at the bottom is estimated as 6m, which is two times of the depth of the steel. It is known from table 3 that the best feeding rate is 1.75-2.0m/s, which makes sure the pure calcium cored wire reach the bottom without easily heaping up.

Tab. 3 – Gasification time and the time used by the pure calcium cored wire reaching the bottom of the molten steel at different feeding rate

FEEDIN GRATE, m/s	GASIFICATION TIME, s	THE TIME USED BY THE PURE CALCIUM CORED WIRE REACHING THE BOTTOM OF THE MOLTEN STEEL ,s
1.50	3.36	4.00
1.75	3.28	3.43
2.00	3.20	3.00
3.00	2.99	2.00
4.00	2.85	1.50
5.00	2.75	1.20

In order to verify this result, a comparative experiment was carried out on the yield of calcium element of pure calcium cored wire at different feeding rate. The results are shown in Fig. 9.

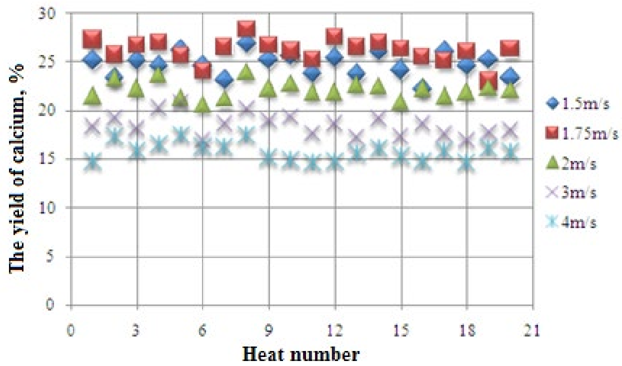


Fig. 9 – The relationship between the different feeding rate of pure calcium cored wire and the yield of calcium

It is known from Fig. 9, when the feeding rate is 1.50m/s, 1.75m/s, 2.00m/s, 3.00m/s, 4.00m/s, the average yield of calcium is 24.7%, 26.1%, 22.1%, 18.4%, and 15.8%.
So, the industrial test of different feeding rate shows that the optimum feeding rate is 1.75m/s, which is in accordance with the numerical simulation results.

CONCLUSION

Using heat transfer 2D finite element model of pure calcium cored wire in molten steel, the temperature changes of pure calcium cored wire in molten steel at different wire feeding rate are calculated, The rules of melting and gasification of calcium core is analyzed, and the optimum feeding rate of pure calcium cored wire is determined combined with industrial test, the conclusions as follows:

1)The junction point of the calcium core and the outer steel sheet is the turning point of the heat transfer, and it is also the limiting step of the heat transfer.

2)When the molten steel temperature is 1570℃, and the feeding rate is 1.50m/s-5.00m/s, the time required for the pure calcium cored wire to reach the melting point is 1.19s-1.43s, and the time to reach the boiling point is 2.75s-3.36s.

3)When the temperature of the calcium core reaches the boiling point 1484℃, and the temperature of the steel sheet of the pure calcium cored wire is 1496℃~1498℃, the steel sheet is in the state of non-melting.

4)The optimum feeding rate is 1.75m/s, and the yield of calcium is 26.1%.

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