

Calcium wire injection in steel melt: Modeling of calcium recovery under industrial operating conditions

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Abstract

A mathematical model has been developed to analyze the melting behaviour of cored wire filled with CaSi and CaFe powders when injected into steel melt under industrial operating conditions. Calcium (Ca) recovery obtained from steel samples under industrial operating conditions at an integrated steel plant has been correlated with the model-predicted distance traversed by the cored wire under those conditions for CaSi and CaFe filled cored wire. Calcium recovery was found to increase as the wire approached the ladle bottom and then decreased as the distance travelled by the cored wire exceeded the bottom of the ladle. Under the industrial operating conditions, the model-predicted distance traversed by the CaSi cored wire was found to lie beyond the ladle bottom for the majority of the industrial heats, which are correlated with the actual calcium recovery values that are estimated from steel samples collected before and after wire injection. It was demonstrated that a higher bath superheat would be required to melt the CaSi cored wire near the ladle bottom than the CaFe cored wire. It was found that the Ca recovery from CaSi cored wire could reach as high as 20–30% when the wire melts at the bottom of the ladle, which is substantially higher than the maximum Ca recovery of 6% observed for CaFe cored wire under similar operating conditions, even when the CaFe wire also melts at the ladle bottom.

Keywords: Cored wire injection; Mathematical model; Calcium recovery; Bath superheat; Steel melt

1. Introduction

Calcium (Ca) is added to liquid steel for inclusion modification. Calcium addition also helps in deep deoxidation and desulphurization of the liquid steel to some extent. The major objectives reported for Ca-treatment include improving castability during continuous casting, enhancing surface quality, achieving better steel cleanliness, and improving mechanical properties—particularly in the transverse and through-thickness directions of cast steel products [1-3].

The calcium (Ca) recovery in the cored wire injection process is relatively higher compared to traditional submerged injection and other Ca addition methods, such as bullet shooting and pouring techniques [4]. Minimal interaction with slag and reduced agitation of the steel bath during cored wire injection further enhance the effectiveness of this process, giving it an advantage over other methods. The powder should be released near the bottom of the ladle to maximize the residence time of calcium and enhance its assimilation into the molten steel. But the things that are not obvious include i) the optimum operating parameters for maximum Ca recovery of wire, ii) how model prediction could be correlated with the actual Ca recovery, estimated from plant data under wide operating conditions. A comprehensive analysis of the dissolution behaviour of cored wire in steel melt, coupled with a plant-scale experimental investigation, can only ensure this.

The parameters influencing the melting and dissolution behaviour of ferroalloys, metallic cylinder, and aluminium wire in molten bath have been studied by several researchers [5-14]. However, only a few works

have been reported on the dissolution behaviour of Ca-bearing cored wire in steel melt. Besides, the melting behaviour of Ca-bearing cored wire has hardly been correlated with Ca recovery, the parameter that directly correlates with inclusion modification. Du Terrail et al. [15] developed a heat transfer model to determine the penetration depth of the wire when injected in a circular trajectory inside the steel melt. They also carried out experiments by placing a thermocouple at three different radial locations in the cored wire to validate the model predictions and found that the dissolution of cored wire is enhanced by an exothermic reaction at the CaSi/casing interface when the temperature of the bath is lower than 1550°C.

Huang et al. [16] developed a three-dimensional CFD simulation model on the FLUENT platform to study the effect of wire speed and wire dimension on the evaporation depth of calcium and mixing efficiency in the argon-stirred ladle. Their findings suggested that the melting time increased by around 0.1 sec when the wire diameter increased by 1 mm. E.I. Castro-Cedeno et al. [17] developed a numerical tool by coupling the ANSYS Fluent CFD code with the thermodynamic code CEQCSI. This tool was applied to industrial configurations to investigate the potential effects of calcium injection on the modification of non-metallic inclusions. Sanyal et al. [18-19] proposed a one-dimensional transient heat transfer model to investigate the impact of operating parameters like wire speed, wire diameter, casing thickness, bath superheat, etc., on the melting behaviour of CaSi cored wire in steel melt. They also studied the impact of slag layer and steel grade on the melting behaviour of the cored wire. The presence of slag was reported to bring in a unique phenomenon of secondary steel shell growth that delayed the wire melting. They further observed that the wire dissolution rate was more sensitive to casing thickness than the wire diameter, and an optimum wire speed was suitable for maximum penetration of the wire in the steel melt.

Basak et al. [20] studied the recovery and efficacy of Ca injection as a function of plant operating variables using dimensional analysis and examined inclusions by scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). They developed a dimensionless correlation of Ca recovery with operating parameters in terms of dimensionless numbers like Biot number, dimensionless bath temperature, and rate of silicon to sulphur transfer from/to CaSi in the melt. More importantly, they reported that an optimum quantity of calcium in the molten steel is needed for the formation of desired inclusions, and there could be significant savings in wire injection by limiting its addition under optimum wire speed. Kumar et al. [21] investigated the Ca recovery and efficiency of CaSi and CaFe cored wire addition in industrial steel melts and mapped the operating parameters for trouble-free casting for industrial operation.

Several studies analyzed the effect of different operating parameters on Ca recovery [20-23]. On the other hand, Sanyal et al. [18-19] have studied the effect of operating parameters on the model-predicted distance traversed by the cored wire. The present study acts as a missing link between the studies mentioned above. The present study correlates the plant-estimated Ca recovery with the model-predicted wire melting data. Subsequently, the model could be used to predict the industrial parameters that will ensure maximum Ca recovery. The study also analyzes, under plant operating conditions, which filling material performs better, and why.

2. Experimental Procedure

Calcium wire injection was performed at the ladle furnace (LF) at the argon rinsing station (ARS) of an integrated steel plant. To achieve homogeneity in both temperature and chemical composition of the molten steel, the molten steel in the ladle was continuously stirred by introducing argon gas through an eccentric bottom nozzle in the ladle, and this stirring was maintained throughout the calcium treatment operation.

Standard “lollypop” samples were taken from the ladle at the argon rinsing station just before the calcium addition in the ladle and from the tundish after calcium treatment. These samples were then analyzed sequentially for elemental composition using an optical emission spectrometer (OES). The initial plant records included details such as the ARS and tundish compositions, the length of calcium wire

injected, bath temperature, and casting conditions. These data were subsequently utilized to estimate the percentage calcium recovery, as well as the liquidus temperature and superheat of the bath. An earlier work of the corresponding author has described the detailed procedure of estimating the Calcium level in the ladle after Ca-treatment, Ca recovery, and bath superheat of industrial heats [21]. For the present study, data from 37 industrial heats (21 CaSi and 16 CaFe) were analyzed, covering cored wire injection speed ranging from 63 to 190 m/min. and steel bath superheat ranging from 50 to 125 °C.

3. Mathematical modelling

3.1. Mathematical Formulation

When cored wire at room temperature comes in contact with the molten steel bath at high temperature (~1600°C) during its injection, a series of complex unsteady-state heat transfer events are initiated. A thin, solidified steel shell forms around the cored wire. A schematic of a cylindrical wire with a solidified steel shell on it after its immersion in liquid steel is depicted in Figure 1. The shell initially grows, and after reaching a maximum, it starts dissolving in the molten bath, and finally, the Ca-bearing powder is released into the bath. The whole process has been studied through a mathematical model of transient one-dimensional heat conduction in cylindrical coordinates with a moving boundary. The present model assumes one-dimensional radial heat transfer by neglecting axial conduction and wire-end melting effects. This assumption is justified because the wire length is much larger than its diameter, the radial thermal diffusion time is considerably much shorter than the axial diffusion time, and heat transfer predominantly occurs through the cylindrical surface of the wire. Furthermore, the end region represents only a very small fraction of the total injected wire length, making its influence on the overall melting time negligible. Therefore, the one-dimensional radial model provides a reasonable approximation for predicting the melting behavior under the investigated operating conditions.

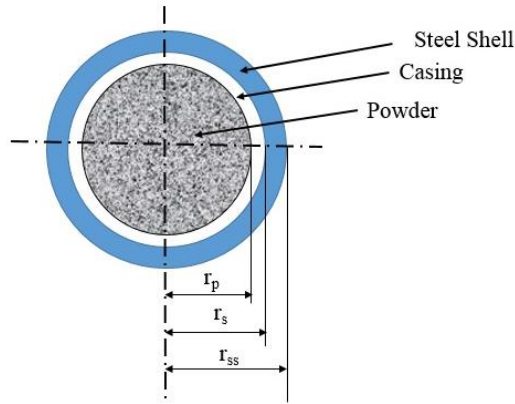


Figure 1. Schematic representation of a cross-section of a cylindrical cored wire with a solidified steel shell on it after its immersion in liquid steel.

3.1.1. Governing Equations

The temperature distribution inside the cylinder-shaped cored wire for a stationary observer can be described by a one-dimensional unsteady-state heat conduction equation (Equation (1)).

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(k r \frac{\partial T}{\partial r} \right) \quad (1)$$

Equation (1) for powder, casing, and the steel shell can be represented as follows:

1. Powder: $0 \leq r \leq r_p, 0 \leq t \leq t_{\text{tot}}$

$$\rho_p C_{p_p} \frac{\partial T}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(k_p r \frac{\partial T}{\partial r} \right) \quad (2)$$

2. Casing: $r_p \leq r \leq r_s, 0 \leq t \leq t_{\text{tot}}$

$$\rho_s C_{p_s} \frac{\partial T}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(k_s r \frac{\partial T}{\partial r} \right) \quad (3)$$

3. Steel shell: $r_s \leq r \leq r_{ss}, 0 \leq t \leq t_{\text{tot}}$

$$\rho_{ss} C_{p_{ss}} \frac{\partial T}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r} \left(k_{ss} r \frac{\partial T}{\partial r} \right) \quad (4)$$

The t_{tot} is the total time up to the point of release of the powder and consists of different time intervals as:

$$t_{\text{tot}} = t_{\text{steel shell freezing}} + t_{\text{steel shell melting}} + t_{\text{casing heating}} + t_{\text{casing melting}} \quad (5)$$

Initial conditions and conditions at different boundaries in the present study are as follows:

3.1.2. Initial conditions

Before immersion, the temperature of the cored wire was taken to be uniform at room temperature (25°C).

Mathematically, $T=25^\circ\text{C}$, when $t = 0$ and $0 \leq r \leq r_s$ (6)

Similarly, the temperature of the liquid bath (T_{lb}) is assumed to be constant during the period of computation, considering minuscule wire addition in a large molten bath.

3.1.3. Boundary conditions

B.C. at center: Equation (7) represents the symmetric condition at the center of the cored wire.

$$0 \leq t \leq t_{\text{tot}}, \quad \frac{\partial T}{\partial r} = 0 \quad (7)$$

B.C at solid/solid interface: Solid/solid interfaces could be powder/casing interface, casing/solidified shell interface. At the solid/solid interface, the heat leaving one solid (Solid-I) should be equal to the heat entering the other solid (Solid-II), which is represented by Equation (8).

$$0 \leq t \leq t_{\text{tot}}, \quad k_I \frac{\partial T}{\partial r} = k_{II} \frac{\partial T}{\partial r} \quad (8)$$

B.C. at solid/liquid interface: Solid/liquid interfaces could be casing/liquid, solidified shell/liquid interface, and Equation (9) represents the heat flux entering the solid is equal to the heat flux reaching the interface through the thermal boundary layer at the solid/liquid interface.

$$k_s \frac{\partial T}{\partial r} = h(T_L - T_S) \quad (9)$$

For the casing/ liquid interface, the surface temperature will represent the casing surface temperature, but in the case of the shell/liquid interface, the surface temperature will represent the liquidus of the liquid bath. The heat transfer coefficient (h) at the solid/liquid interface has been estimated from the following dimensionless correlations [19].

$$\text{Nusselt Number : } Nu_L = 0.0296 Re^{0.8} Pr^{0.33} \quad \text{if } Re > 10^5 \quad (10)$$

$$Nu_L = 0.4 Re^{0.5} Pr^{0.453} \quad \text{if } Re < 10^5 \quad (11)$$

$$\int_w^e \int_t^{t+\Delta t} \rho C_p \frac{\partial T}{\partial t} \partial r \partial t = \int_w^e \int_t^{t+\Delta t} \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) \partial r \partial t \quad (16)$$

Some simplified piecewise temperature profiles over grid spacing and time interval are assumed to evaluate the different differential and integral terms, to finally translate the above integral (Equation (16)) into a linear algebraic equation with grid point temperatures as the only unknown, called the discretization. Assuming a piecewise linear profile for temperature over grid spacing in the radial direction, and assuming current temperature to prevail over the time step (implicit scheme), finally, the following discretization equation is obtained:

$$\left(\frac{k_e r_e}{(\partial r)_e} + \frac{k_w r_w}{(\partial r)_w} + \rho C_p \frac{(r_e^2 - r_w^2)}{2\Delta t} \right) T_p = \frac{k_e r_e}{(\partial r)_e} T_E + \frac{k_w r_w}{(\partial r)_w} T_W + \rho C_p \frac{(r_e^2 - r_w^2)}{2\Delta t} T_p^o \quad (17)$$

For the grid point at the center (West Boundary): The boundary CV is considered half, as shown in Figure 2. For the west boundary, the integration of the governing equation over the half CV (cc'd'd) can be written as follows:

$$\int_p^e \int_t^{t+\Delta t} \rho C_p \frac{\partial T}{\partial t} \partial r \partial t = \int_p^e \int_t^{t+\Delta t} \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) \partial r \partial t \quad (18)$$

Maintaining a similar piecewise profile for temperature with radial distance and time as mentioned earlier, and also applying a no-flux boundary condition as in Equation (7), the final discretized equation may be derived as:

$$\left(\frac{k_e r_e}{(\partial r)_e} + \rho C_p \frac{r_e^2}{2\Delta t} \right) T_p = \frac{k_e r_e}{(\partial r)_e} T_E + \rho C_p \frac{r_e^2}{2\Delta t} T_p^o \quad (19)$$

For the grid point at the surface (East Boundary): Similarly, by integrating the governing equation over the half CV (ee'f'f), and applying the boundary condition given by Equation (9), the discretized equation at the east boundary may be obtained as:

$$\left(\frac{k_w r_w}{(\partial r)_w} + \rho C_p \frac{(r_p^2 - r_w^2)}{2\Delta t} + r_p \cdot h \right) T_p = \frac{k_w r_w}{(\partial r)_w} T_W + \rho C_p \frac{(r_p^2 - r_w^2)}{2\Delta t} T_p^o + r_p \cdot h \cdot T_{lb} \quad (20)$$

Equations (17), (19), and (20) can be simply represented by Equations (21) and (22) in the form of a Tridiagonal Matrix, which are solved by the tridiagonal matrix algorithm (TDMA). Values of the coefficients of these equations are mentioned in Table 1.

$$A_p T_p = A_E T_E + A_W T_W + A_p^o T_p^o \quad (21)$$

In terms of grid numbers (i=1 to N)

$$b_i T_i + a_i T_{i-1} + c_i T_{i+1} = d_i \quad (22)$$

Where a, b, and c represent $-A_E$, A_p , and $-A_W$ of Equation (22), respectively.

Table 1. Coefficients of the equations represented by Equation (22).

Coefficients	Grid point at west boundary (i=1)	Interior grid points (i=2 to N-1)	Grid point at the east boundary (i=N)
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$$h(T_{lb}-T_L)A_{aa'} - \left\{ k_{ss} \frac{(T_L-T_p)}{\delta} \right\} A_{bb'} = V_{\delta} \cdot \rho_{ss} \cdot \frac{[\Delta H_f + C_p(T_L-T_p)]}{\Delta t} \quad (24)$$

or,

$$h(T_{lb}-T_L)(r_p + \delta) - \left\{ k_{ss} \frac{(T_L-T_p)}{\delta} \right\} r_p = \left(r_p + \frac{\delta}{2} \right) \delta \cdot \rho_{ss} \cdot \frac{[\Delta H_f + C_p(T_L-T_p)]}{\Delta t} \quad (25)$$

In Equation (25), the value of δ is the only unknown parameter, as the temperature T_p has already been calculated. Thus, Equation (25) is used to estimate the value of δ . The sign of δ will determine whether the shell is growing/solidifying (δ is positive) or the shell is melting (δ is negative). Therefore, δ is added/subtracted to the value of the existing radius of the wire, r_p

If δ exceeds the value of grid spacing (Δr), then a new grid point will be added at a Δr distance from the previous surface grid point, and it becomes the new surface grid point. The current temperature of the new surface grid point P is calculated by linear interpolation (Equation (26)).

$$T_p = \frac{T_L \Delta r + T_w \delta}{\Delta r + \delta} \quad (26)$$

Where, T_p = Temperature of the newly formed surface grid point (East Boundary), P

T_w = Temperature of the new W grid point (i.e., the old surface grid point P), and

δ = The new value of δ

Whereas, if δ shrinks by the value of grid spacing (Δr), then a new grid point will be subtracted at a Δr distance from the previous surface grid point, and it becomes the new surface grid point. The old W grid point now becomes the new surface grid point P, and the temperature of the new grid point P is the temperature of the last W grid point.

Heat balance for shell growth over a solidified shell: After estimating the value of shell thickness δ over casing with (if δ exceeds Δr) or without (if δ does not exceed Δr) a new grid point, the temperature of each grid point is calculated at the present step. Then, the value of shell thickness δ^* grown/shrinks over already solidified shell δ is computed by performing a heat balance over the surface face grid point, as illustrated in Figure 4.

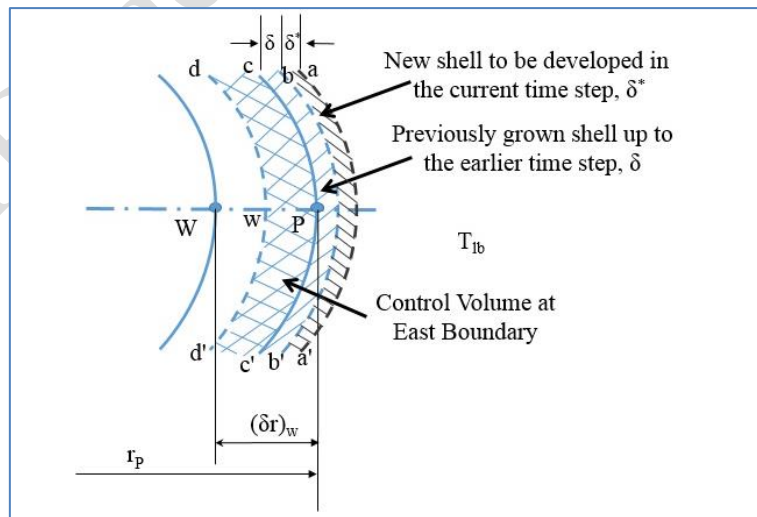


Figure 4. Schematic representation of the heat balance for shell growth over already solidified shell.

Heat balance statement:

$$\left(\begin{array}{l} \text{Heat in through face aa'} \\ - \text{Heat out through face cc'} \end{array} \right) = \left(\begin{array}{l} \text{Sensible Heat + Heat released by} \\ \text{solidification of shell of thickness } \delta^* \\ \text{over already solidified shell of thickness } \delta \end{array} \right) \quad (27)$$

Mathematically, the heat balance may be represented as:

$$h(T_{lb} - T_L)(r_p + \delta + \delta^*) - \left\{ k_{ss} \frac{(T_L - T_p)}{(\delta + \delta^*)} \right\} r_p = \left(r_p + \delta + \frac{\delta^*}{2} \right) \delta^* \cdot \rho_{ss} \cdot \frac{[\Delta H_f + C_p(T_L - T_p)]}{\Delta t} \quad (28)$$

The value of δ^* , the only unknown parameter, is estimated using Equation (28) as the temperature T_p has already been calculated in the current time step. Solidification or melting could be identified by looking at the sign of δ^* .

3.4. Methodology

The following steps were followed for the calculation:

1. Calculate the temperature from the center of the cored wire to its exterior surface without considering any shell growth. The boundary condition at the surface follows Equation (9). Discretized equations given by Table 1 are solved using TDMA [25].
2. Calculate the shell growth at the surface and the shell thickness δ based on Equation (25).
3. If the developed shell thickness exceeds Δr , add a new grid point (new terminal grid point) at a distance Δr from the old surface grid point. The temperature at the new terminal point may be calculated by linear interpolation as defined in Equation (26). The new terminal point may be engraved in the solidified shell or may be exposed to the liquid. If the new terminal point is engraved inside the shell, then the heat flux reaching the surface CV is by conduction through the solidified shell, which may be represented as: $\frac{K_s}{\delta}(T_{lb} - T_s)$, which is equivalent to the terminal point exposed to liquid: $h(T_L - T_s)$ where $h = \frac{K_s}{\delta}$, $T_L = T_{lb}$ (bath liquidus) and T_s is the temperature of the terminal grid point within the solidified shell.
4. Recalculate temperature for the next time step with or without the new terminal point using the discretized equation (Equation (22)), with appropriate change in h and T_L as mentioned above.
5. Calculate the shell growth in the current time step using Equation (28) and repeat steps 3 to 4 until the casing is exposed to liquid. Please note that δ^* will be positive as long as the shell grows (shell growth will continue as long as the heat flux reaching the terminal CV from the liquid side is lower than the heat flux moving towards the interior of the wire). After attaining the maximum thickness, the shell will shrink (δ^* negative) due to melting (heat flux reaching the surface of the terminal grid point is more than that leaving towards the core of the wire).
6. Continue the transient calculation of the temperature profile in the wire till the casing dissolves.

3.5. Validation of the model

Before comparing the model with available work on the moving boundary problem, the mathematical model must be capable of simulating the flow of heat in a static cylinder. The melting of static metallic cylinders in a liquid steel bath has been simulated in the mathematical model. Figure 5(a) compares the variation in the radius of a 3.81 cm diameter niobium cylinder predicted by the present model with the

corresponding results reported in the literature. Similarly, Figure 5(b) compares the predicted temperature at the center of a 2.54 cm diameter tantalum cylinder during its melting in a liquid steel bath at 1600 °C with the available literature data. After validating the model with a static cylinder, the model is modified to incorporate the moving boundary problem (melting and freezing). The prediction of this model with a moving boundary problem was then verified with the data available in the literature, as shown in Figure 6.

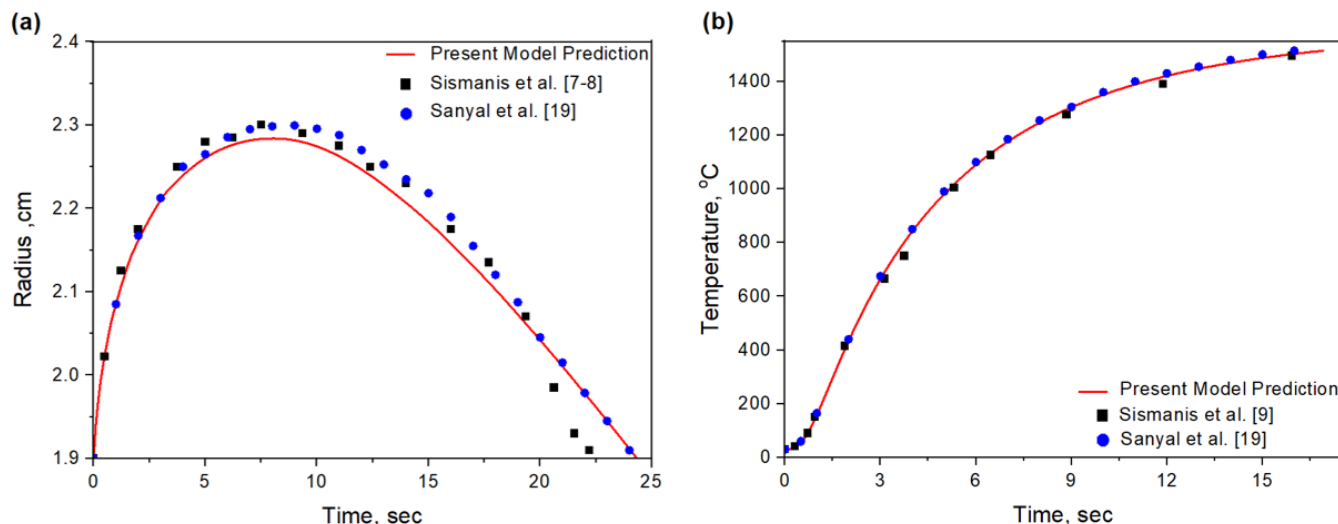


Figure 5. Comparison of (a) the variation in the radius of a 3.81 cm diameter niobium cylinder predicted by the present model, and (b) the temperature at the center of a 2.54 cm diameter tantalum cylinder during its dissolution in a liquid steel bath at 1600°C, with the corresponding results reported in the literature.

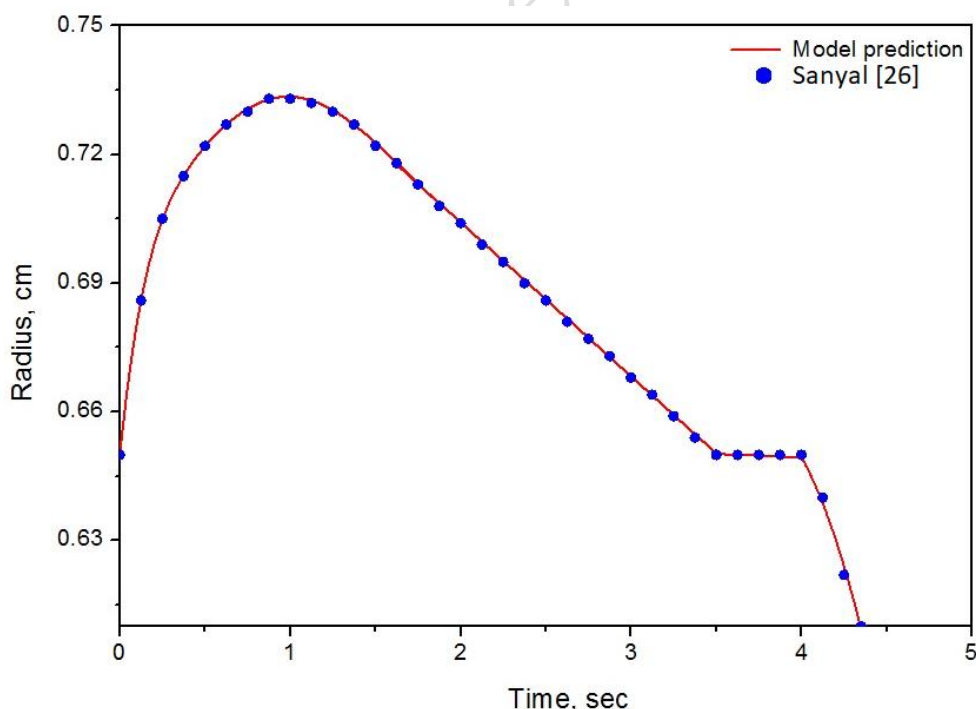


Figure 6. Variation in radius of CaSi-filled cored wire of 13 mm diameter and 0.4 mm casing thickness with time when immersed with a speed of 400 cm sec⁻¹ in liquid steel at 1550°C.

4. Results and Discussions

This section is divided into two subsections. In the first subsection, model predictions for the change in radius of casing with time and dissolution time with wire speed have been studied for different Ca-bearing filler materials like CaSi, CaFe, and Pure Ca. In a later subsection, a relationship between the distance travelled by the CaSi and CaFe cored wire in a molten steel bath with industrial operating conditions (wide range of wire speed and bath temperature) has been presented. Finally, a correlation between experimental Ca recovery of cored wires and predicted distance travelled by cored wire in steel melt has been demonstrated.

4.1. Model Predictions

4.1.1. Model predictions for change in radius with time

The thermo-physical properties of the liquid bath, casing, and three filler materials (CaSi, CaFe, and pure Ca) used in the present study are presented in Table 2. Such properties of filling powders have been calculated as the weighted average of those of pure elements present in those filler powders at 25°C. The compositions of the filler powders are shown in Table 3.

Table 2. Thermo-physical properties of liquid steel, cored wire casing, and filler materials of cored wire.

Property	Units	Liquid Steel [26]	Cored wire casing [26]	CaSi	Pure Ca	CaFe
Density, ρ	gm cc ⁻¹	7.05 (at 1600°C)	7.268 (at 25°C)	2.67	1.59	5.97
Thermal conductivity, k	J cm ⁻¹ sec ⁻¹ °C ⁻¹	0.403 (at melting point)	0.346 (at melting point)	1.59	2.01	1.17
Specific heat, C_p	J gm ⁻¹ °C ⁻¹	0.795	0.794	0.66	0.65	0.51
Dynamic viscosity, μ	gm cm ⁻¹ sec ⁻¹	0.0532	-	-	-	-
Latent heat of fusion, ΔH_f	J gm ⁻¹	274	274	-	-	-
Melting Temperature	°C	1525	1520	-	-	-

Table 3. The composition of different filler materials of cored wire is considered in the present study.

Elements	CaSi	Pure Ca	CaFe
Ca (wt.%)	30.86	99.00	29.67
Fe (wt.%)	10.40	0.50	69.75
Si (wt.%)	58.05	0.00	0.00
Al (wt.%)	0.69	0.50	0.58

Transient evolution of wire radius during the solidification and subsequent melting periods for CaSi, CaFe, and pure Ca-filled cored wires is depicted in Figure 7(a). All three curves show similar behaviour. The radius first increases for shell growth and then decreases for shell melting, and finally, the curve passes through a small plateau indicating a period of casing heating without any change in radius. It is also found that CaFe has the minimum time for its melting, which may be attributed to its lower thermal conductivity

compared to CaSi and pure Ca. It is further observed that pure Ca attains the maximum shell growth, which may be attributed to its higher thermal conductivity. The higher thermal conductivity of pure Ca promotes more rapid heat transfer from the surrounding molten steel into the cored wire during the initial stage of heating. As a result, molten steel solidifies on the outer surface of the wire casing, forming a thicker steel shell around the pure Ca cored wire than around the CaSi and CaFe wires. The thicker shell delays complete melting of the wire casing and consequently shifts the calcium release location to a greater immersion depth. In contrast, the relatively thinner steel shell formed around the CaSi and CaFe wires allows the casing to melt more readily, resulting in earlier casing melting and shallower powder release depths compared with the pure Ca wire. For the present operating conditions, the pure Ca, CaSi, and CaFe cored wires require 5.66, 4.56, and 4.13 sec, respectively, to release the Ca-bearing powder.

When steel solidifies on the casing, an interfacial resistance develops between the casing and the solidified layer due to imperfect thermal contact between them. For the present study, the magnitude of this resistance is taken as $1.9 \text{ cm}^2\text{s}^\circ\text{CJ}^{-1}$ [19]. Once the frozen layer is melted back completely, this contact resistance vanishes, and convective heat flux is implied at the casing/liquid interface. Figure 7(b) shows the variation in temperature at the center and powder/casing interface of cored wire with time. The temperature at the center of the CaFe-filled cored wire increases slowly compared to the CaSi and pure Ca-filled cored wire. To reach a temperature 1400°C at the center of the cored wire, pure Ca, CaSi, and CaFe cored wires take 0.86, 1.21, and 2.14 sec, respectively, which reflects their decreasing thermal conductivity in this order.

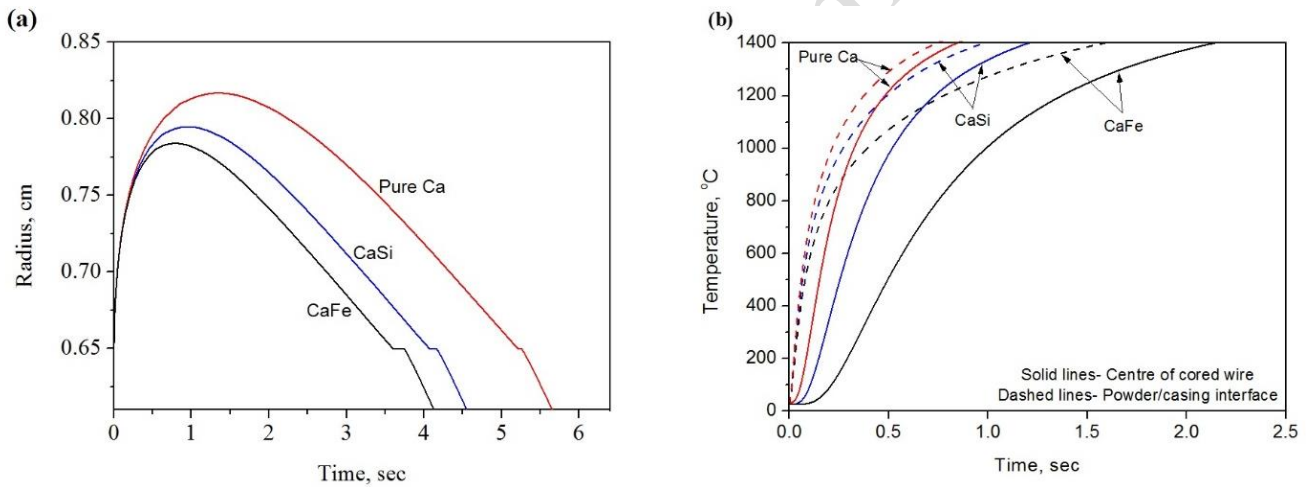


Figure 7. Variation in (a) radius and (b) temperature at center and powder/casing interface of cored wire of 13 mm diameter and 0.4 mm casing thickness with time (wire speed-300 cm/sec and bath temperature- 1600°C).

Since the thermo-physical properties of materials, such as thermal conductivity and specific heat capacity, are temperature dependent, a sensitivity analysis was carried out for the CaSi cored wire, as shown in Figure 8. Figure 8(a) compares the variation in the radius of the CaSi cored wire, while Figure 8(b) shows the temperature evolution at the centre of the CaSi cored wire with time. In Figure 8, the solid lines represent the simulation results obtained using constant thermo-physical properties of molten steel, the cored wire casing, and the CaSi core material, as listed in Table 2. In contrast, the dashed lines correspond to simulations performed using temperature-dependent specific heat capacity and thermal conductivity for the cored wire casing and solidified steel shell, and the CaSi powder. The temperature-dependent thermo-physical properties employed in the numerical model were sourced from the literature. Specifically, the temperature-dependent specific heat capacity and thermal conductivity of the CaSi powder were taken from Sanyal's thesis [26], whereas the corresponding properties of the cored wire casing and the solidified steel shell were adopted from Gaskell [27] and Castro-Cedeno et al. [14], respectively. Since reliable

temperature-dependent thermo-physical property data for CaFe powder and pure Ca are not readily available in the literature, a similar comparison could not be performed for CaFe and pure Ca cored wires. As evident from Figure 8, the differences in the model-predicted wire radius and centre temperature between the constant thermo-physical properties and temperature-dependent thermo-physical properties models were found to be below 5%. This indicates that the consideration of constant thermo-physical properties for analysis has only a minor influence on the predicted melting behaviour of the CaSi cored wire. Therefore, it is reasonable to expect that a similar trend would be observed for CaFe and pure Ca cored wires, and the results obtained using constant thermo-physical properties are sufficiently satisfactory to represent the overall melting behaviour and release characteristics of these cored wires.

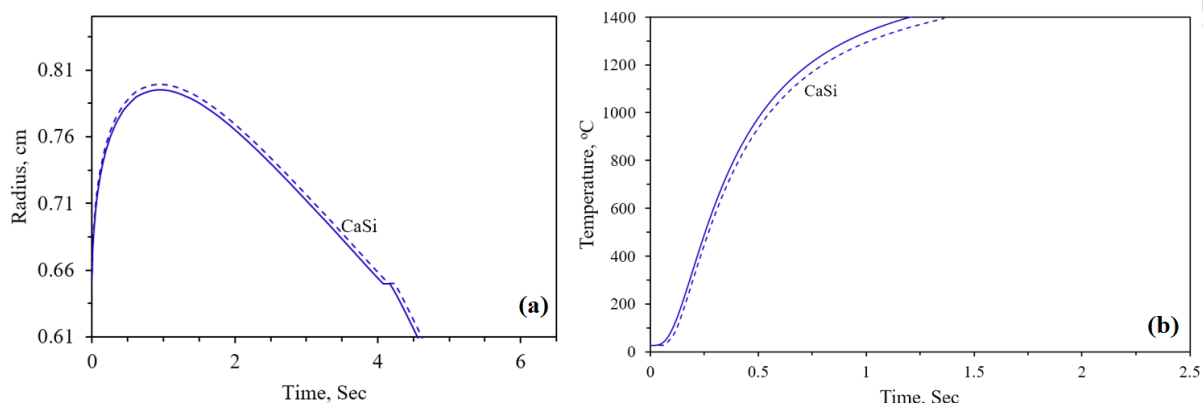


Figure 8. Variation in (a) the radius and (b) the center temperature of a 13 mm diameter CaSi cored wire with a 0.4 mm casing thickness as a function of time. Solid lines represent simulations performed using the constant thermo-physical properties listed in Table 2, while dashed lines represent simulations using temperature-dependent thermo-physical properties.

4.1.2. Model predictions for dissolution time with wire speed

The effect of wire speed on the dissolution time and thus on the distance traversed by the wire before its melting has been shown in Figure 9 for CaSi, CaFe, and pure Ca-filled cored wire. It is found that melting time decreases with the increase in wire speed, which may be attributed to the enhanced heat transfer efficiency at the solid/liquid thermal boundary layer. However, a reduction in melting time due to this factor does not necessarily result in a corresponding decrease in the distance travelled. As shown in Figure 9, initially, the distance traversed by the wire increases with wire speed, and after reaching a maximum at a certain speed, it again decreases. The initial increase may be understood by the general conviction that a higher speed will take the wire to a larger distance. But with further increase in speed, the melting time also decreases as discussed above. The dominance of these two contradictory factors decides the optimum speed for maximum distance traversed by the wire.

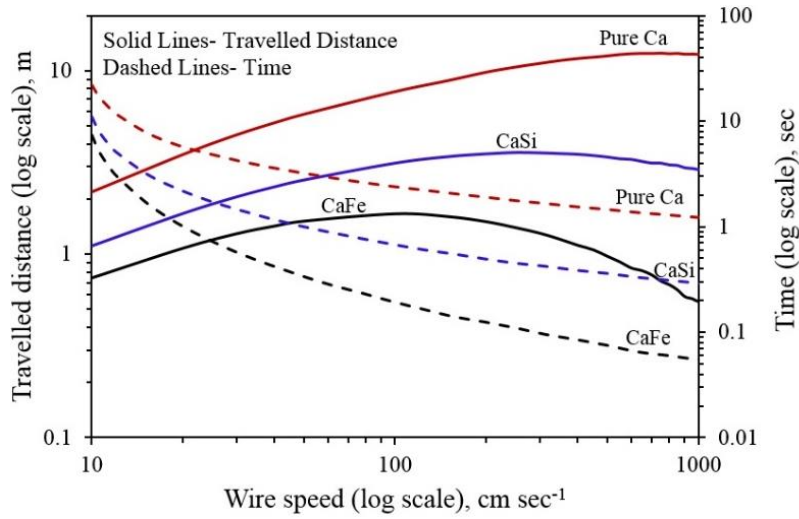


Figure 9. Predicted distance traversed and melting time of 13 mm wire at different wire speeds (bath temperature-1600°C).

4.2. Plant data correlation with model predictions

In the present study, it is aimed to correlate the predicted distance travelled by the cored wire in the steel bath before its melting to the estimated Ca recovery based on plant data. To establish such a correlation, the distance travelled by the cored wire in each industrial heat is calculated separately using the wire speed and bath temperature of that industrial heat. Then, the predicted distance traversed by the cored wire is mapped against ranges of wire speeds and bath superheats of actual industrial heats for CaSi and CaFe trials. All predictions are carried out based on actual wire dimensions used in the integrated steel plant (13 mm wire diameter with 0.68 mm casing thickness). The ladle dimensions used for calculations were those of actual plant data (142.5 tons and height 3 meters).

4.2.1. Effect of wire speed on distance travelled

The effect of cored wire speed on the predicted distance traveled by the wire before releasing Ca-bearing powder in steel melt, under actual plant conditions with a bath superheat ranging from 50°C to 125°C, is shown in Figure 10. Figure 10 represents both the CaSi trial and the CaFe trial heats. It is observed that for a similar range of bath superheat, the CaSi-filled cored wire travelled a greater distance than the CaFe-filled cored wire. More interestingly, it may be observed that the distance traversed by the CaSi wire under these industrial practices is always higher than the ladle bottom, except in a few cases, which means that the CaSi wire did not melt, even reaching the ladle bottom under these industrial operating conditions. If the wire does not melt after reaching the bottom, it may either spiral or revert upward, and in both of these cases, the powder released will be up in the bath, yielding less assimilation time and lower recovery of calcium. From Figure 10, it is observed that under similar operating conditions, in several heats the CaFe wire melts above the ladle bottom, and in some cases it also exceeds the ladle bottom before its melting. The late melting of CaSi wire compared to CaFe wire may be attributed to the higher thermal conductivity of CaSi powder as discussed earlier in sub-section 4.1.1.

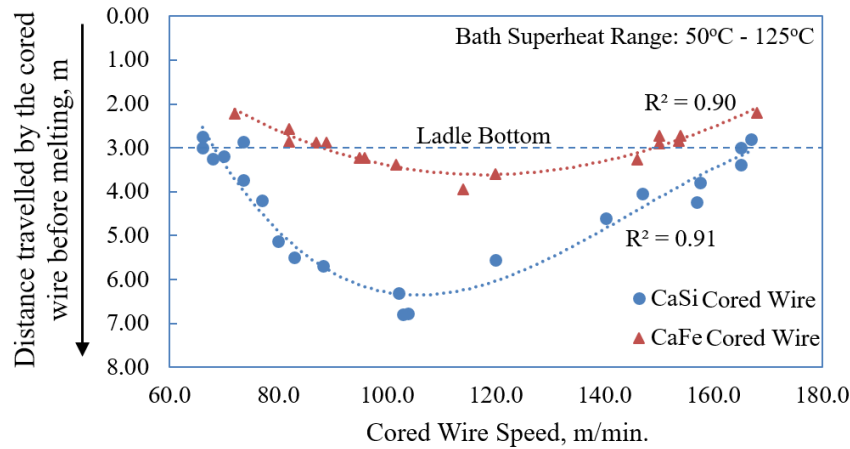


Figure 10. Model-predicted distance travelled by CaSi and CaFe cored wires before melting as a function of wire speed under industrial operating conditions with bath superheat ranging from 50°C to 125°C.

4.2.2. Effect of bath superheat on distance travelled

Figure 11 shows similar plots of distance traversed by CaSi and CaFe wires for different bath superheats. It is again revealed that under industrial operating conditions, the distance travelled by the CaSi wire always exceeds the ladle bottom. On the contrary, the CaFe wire data shows more or less equal distribution on either side of the ladle bottom. It may further be noted that to melt the CaSi wire near the ladle bottom under the existing range of wire speed, higher bath superheat at 110°C is required compared to that of the CaFe wire, which is only 95°C. Therefore, CaFe addition appears to be the energy-efficient option for wire injection in steel melt, which reaches the ladle bottom at lower superheat. However, due to the lower inherent recovery of calcium for CaFe powder compared to CaSi powder, the former does not get an edge.

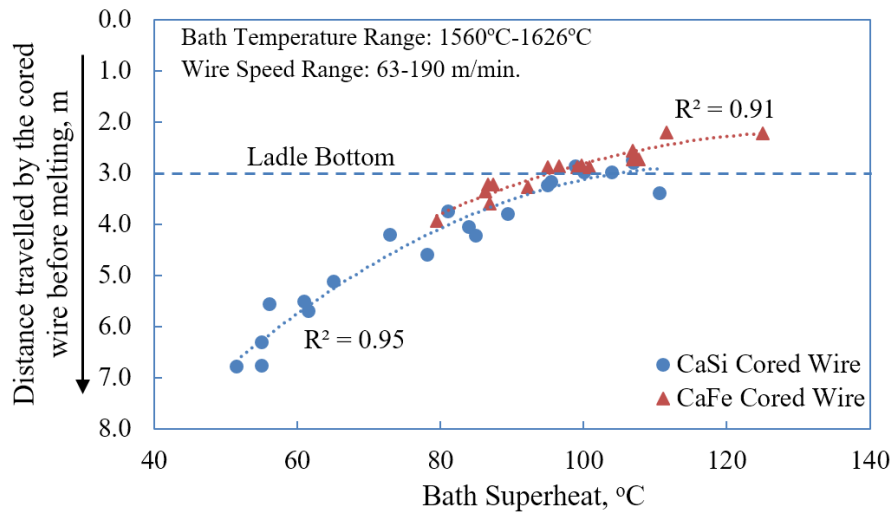


Figure 11. Model-predicted distance travelled by CaSi and CaFe cored wires before melting as a function of bath superheat speed under industrial operating conditions, with bath temperature ranging from 50°C to 125°C and wire speed ranging from 63 m/min to 190 m/min.

4.3. Correlation between experimental Ca Recovery and predicted distance travelled

The correlation between the model-predicted distance travelled by the cored wire before releasing Ca-bearing powder in steel melt and the percentage calcium (Ca) recovery under industrial operating conditions—covering a wide range of wire speeds and bath superheat—is depicted in Figure 12.

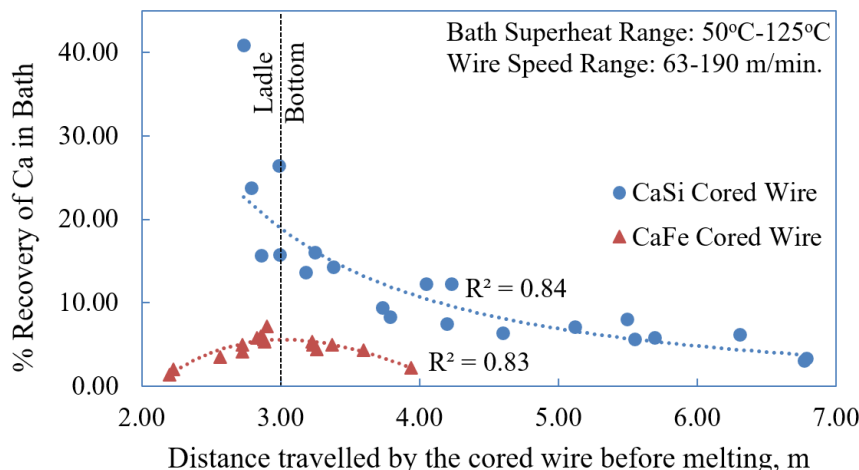


Figure 12. Percentage recovery of Ca in bath of CaSi and CaFe cored wires as a function of predicted distance travelled before melting under industrial operating conditions with bath superheat ranging from 50°C to 125°C and wire speed ranging from 63 m/min to 190 m/min.

From Figure 12, it is seen that the distance traversed by the CaSi cored wire always exceeds the ladle bottom under industrial operating conditions, except for a few cases with a corresponding monotonic decrease in the Ca recovery. For CaFe wire, data are found spread on either side of the ladle bottom, and it is clearly seen that recovery passes through a maximum when the CaFe wire is melted nearer to the ladle bottom. It may be noted that the recovery of calcium for CaSi is about one order of magnitude higher than that of CaFe wire. It is found that the Ca recovery of CaSi could be as high as 20-30 % when the wire melts at the ladle bottom, which is much higher than that of CaFe wire at its best (recovery = 6%) when it melts at the ladle bottom. But the Ca recovery of CaSi wire reaches a low value of the order of 5 only under unfavourable existing operating parameters that draw the wire a longer distance exceeding the ladle bottom before its melting.

The present model predicts the melting behaviour and release depth of the cored wire based on heat transfer analysis. Although a greater release depth generally increases the residence time of Ca in molten steel, thereby favoring improved Ca-recovery, the overall recovery is governed by several metallurgical phenomena as well, including calcium vaporization, oxidation, desulfurization, inclusion modification, and slag-metal interactions. In the case of CaSi cored wire, Ca and Si are present as a CaSi alloy, and the dissolution of Ca from the CaSi alloy is relatively slow because Si reduces the activity of Ca, suppresses its vaporization, and lowers the dissolved oxygen content through deoxidation, thereby enhancing Ca-recovery. This effect becomes more pronounced in steels containing higher dissolved Si, where the diffusion of Si from the CaSi alloy into the molten steel is hindered by the reduced Si concentration gradient. Consequently, Si remains in the CaSi alloy for a longer duration, which further delays the release and dissolution of Ca into the molten steel, minimizes vaporization losses, and improves Ca-recovery. In contrast, CaFe cored wire consists of a mechanical mixture of Ca and Fe powders rather than a chemical alloy. Since Fe dissolves rapidly in the molten steel, Ca is released at an earlier stage and, owing to its high vapor pressure and the absence of the stabilizing influence of Si, vaporizes more readily, resulting in lower Ca-recovery than that achieved with CaSi cored wire. Therefore, while the present model reliably predicts the melting behaviour and release depth of cored wires, the predicted release depth should be regarded as

one of several important factors governing Ca-recovery rather than its sole controlling mechanism. A comprehensive prediction of Ca-recovery would require consideration of the coupled thermodynamic and kinetic phenomena associated with calcium dissolution, vaporization, oxidation, desulfurization, inclusion modification, and slag–metal interactions.

5. Conclusions

1. A mathematical model has been developed to study the melting behaviour of cored wire additions in the steel bath and validated with published work available in the literature.
2. The model was used to predict the distance traversed by the cored wires before melting under industrial operating conditions, considering wire injection speed in the range of 63–190 m/min. and molten bath superheat of 50–125°C. Analysis of 37 industrial heats (21 CaSi and 16 CaFe) showed that the distance traversed by the CaSi wire always exceeded the ladle bottom, while CaFe data remained on either side of the ladle bottom.
3. It was observed that the bath superheat required for melting of CaSi wire near the ladle bottom under industrial operating conditions practiced in an integrated steel plant was higher (110°C) compared to that of CaFe wire (95°C). Although CaFe addition may be energy efficient under said industrial practice, the inherent lower recovery of CaFe powder loses its edge over CaSi powder.
4. A correlation has been established between the model-predicted distance traversed by the wire and the experimentally estimated calcium (Ca) recovery. Ca recovery is found to be maximum only when the wire releases powder closer to the bottom of the ladle. Ca recovery decreased when the cored wire either melted before reaching the bottom or did not melt even after reaching the bottom of the ladle.
5. It is found that the Ca recovery of CaSi could be as high as 20–30% when the wire melts at the ladle bottom, which is much higher than that of CaFe wire at its best (recovery = 6%) when it melts at the ladle bottom. But the Ca recovery of CaSi wire reaches a low value of the order of 5 only under unfavourable existing operating parameters that draw the wire a longer distance exceeding the ladle bottom before its melting.

Conflicts of interest

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This article has no associated data generated and cannot be disclosed due to legal/ethical/other reasons.

Author contribution statement

Conceptualization, N.K., S.S. and B.K.; Methodology, N.K. and B.K.; Software, N.K., S.S. and B.K.; Validation, N.K. and B.K.; Formal Analysis, N.K.; Investigation, S.S. and B.K.; Resources, S.S. and B.K.; Data Curation, N.K., S.S. and B.K.; Writing – Original Draft Preparation, N.K.; Writing – Review & Editing, S.S. and B.K.; Visualization, B.K.; Supervision, S.S. and B.K.; Project Administration, B.K.;

Nomenclature

h	Heat transfer coefficient ($\text{J s}^{-1} \text{cm}^{-2} \text{ }^{\circ}\text{C}^{-1}$)
L	Bath height (cm)
T	Temperature ($^{\circ}\text{C}$)
T_L	Liquidus temperature of steel ($^{\circ}\text{C}$)
T_{lb}	Temperature of the liquid steel ($^{\circ}\text{C}$)
ρ	Density (gm cm^{-3})
C_p	Specific heat capacity ($\text{J gm}^{-1} \text{ }^{\circ}\text{C}^{-1}$)
t	Time (s)
r	Variable radius (cm)
Δt	Time step (s)
Δr	Grid spacing (cm)
V	Wire injection speed (cm s^{-1})
A	Surface area (cm^2)
ΔH_f	Latent heat of fusion (J gm^{-1})
T_p	Temperature at grid Point 'P' at current time step ($^{\circ}\text{C}$)
T_p^0	Temperature at grid Point 'P' at previous time step ($^{\circ}\text{C}$)
k	Thermal conductivity ($\text{J s}^{-1} \text{cm}^{-1} \text{ }^{\circ}\text{C}^{-1}$ or $\text{W cm}^{-1} \text{ }^{\circ}\text{C}^{-1}$)
k_{ss}	Thermal conductivity of the solidified shell ($\text{J s}^{-1} \text{cm}^{-1} \text{ }^{\circ}\text{C}^{-1}$ or $\text{W cm}^{-1} \text{ }^{\circ}\text{C}^{-1}$)
r_e	Radius of the wire up to the east boundary of the concerned CV (cm)
r_w	Radius of the wire up to the west boundary of the concerned CV (cm)
r_p	Radius of the wire up to the concerned grid point (cm)
$(\delta r)_e$	Spacing between the concerned grid point and the next grid point (cm)
$(\delta r)_w$	Spacing between the concerned grid point and the previous grid point (cm)
μ	Dynamic viscosity of liquid steel ($\text{gm cm}^{-1} \text{s}^{-1}$)
V_{δ^*}	Volume of the solid added or depleted in the current time step (cm^3)
δ	Thickness of the shell already present before the current time step (cm)
δ^*	Thickness of the solid added or depleted in the current time step (cm)

Subscripts

p:	Powder	ss:	Steel shell
s:	Casing	tot:	Total

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