Modeling of Ladle Refining Process Considering Mixing and Chemical Reaction

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A ladle furnace (LF) refining process model is proposed considering both steel mixing and multiphase chemical reactions. In the model, the LF, together with the melts, is divided into a finite number of tanks according to the tank-in-series model. The tank number is determined by simulations of the model with varied tanks and compared with the empirical mixing time. The “effective equilibrium reaction zone (EERZ)” method is used to describe the kinetics of multiphase reactions. The thermodynamic library—ChemApp—is applied to link the model to thermodynamic database. Steel/sludge reaction, lining dissolution, alloy addition, and air absorption are considered. Using the model, an industrial LF treatment process is simulated and the reasonability of the predicted compositions of steel, slag, and inclusions is illustrated by comparing with measurements. The inhomogeneity of the steel and inclusion concentrations in different tanks are shown.

1. Introduction

Ladle furnaces (LF) are the most common installations in the secondary refining of steel. In the LF treatment, steel reheating, alloying, deoxidation, desulfurization, and inclusion modification can be realized. The stirring of steel by Ar purging favors the homogenization, inclusion removal, and steel/sludge reactions. The LF refining process therefore involves multiphysical phenomena and multiphase reactions. Computational modeling can offer an efficient and useful approach to investigate the process.

A number of mathematical models have been developed to simulate the LF treatment process, as shown in Table 1. Peter et al. proposed a model on tracking the changes of steel and slag compositions based on Metsim and FactSage.\(^1\)–\(^3\) In addition to the steel/sludge reaction, flux addition and air absorption were considered. By comparing the predicted composition of steel and slag with the industrial data, the relationship of the overall steel mass transfer coefficient and stirring energy was defined. It was suggested that the steel/sludge reaction rate depends on the bulk transport of steel to the interface. Graham and Irons developed a model to control the ladle metallurgy process.\(^4\) For the steel/sludge reaction, the model considered different mass transfer coefficients for different steel and slag components. The mass transfer coefficients were extensively fit to the experimental data. A unified mass transfer coefficient of steel elements was defined as a function of stirring energy. Harada et al. reported a kinetic model to predict the compositions of metal, slag, and inclusion during ladle refining.\(^5\) In the model, the interface and bulk zones were defined for both steel and slag phases while they were circulated by argon gas stirring. The interface zones were similar with the reaction layers. The mass transfer coefficient in steel relied on the stirring energy, whereas the mass transfer coefficient in slag depended on the diffusivity of the species and steel mass transfer. At each step, the thermodynamic equilibrium at the metal/slag interface was calculated using ChemApp and FactSage.\(^6\) In the calculation, the constant ratios of slag entrainment into molten steel, agglomeration of inclusion, and floatation of inclusion into slag were assumed. The simulation results including the composition of steel, slag, and inclusions were in good agreement with the operational results published by Graham et al.\(^4\) Van Ende et al. proposed a kinetic LF process simulation model by applying the “effective equilibrium reaction zone (EERZ)” method and a FactSage Macro process.\(^7\) The reactions and operations in the LF were analyzed and selectively considered. The heat transfer between steel/sludge and steel/refractory were considered and caused temperature changes. An empirical stirring energy-dependent mass transfer coefficient was applied to the model. The calculated results were validated by the industrial data from Graham et al.\(^4\) To study the inclusion development during ladle treatment, Scheller and Shu developed a comprehensive model considering gas stirring and mixing, steel/sludge reaction, inclusion separation, and interaction of lining with steel and slag.\(^8\) The tank series recirculation model was adopted to calculate the mixing in the ladle. The ladle together with the melt was divided into three ring tanks and the plume as the fourth tank and the melt was circulated and mixed. The parameters for the calculation were individually selected based on industrial experience. The predicted inclusion development and compositions of steel and slag agreed well with the industrial practice from 210 and 30 ton ladle treatment. Additionally, similar models were also developed by the researchers with the specified targets due to
Table 1. The summary of the developed models of ladle refining process.

| Authors      | Year | Thermodynamics | Kinetics                              | Annotations                                           |
|--------------|------|----------------|---------------------------------------|------------------------------------------------------|
| Peter et al. | 2005 | FactSage/Metsim | Double film theory                    | Stirring-dependent mass transfer coefficient of steel, obtained by fitting compositions of steel and slag |
| Conejo et al.| 2007 | FactSage/empirical | Double film theory                  | Stirring-dependent mass transfer coefficient of steel, mass transfer coefficient of slag has the same magnitude as that of steel |
| Graham and Irons | 2009 | Empirical       | Double film theory                    | Stirring-dependent mass transfer coefficient of steel, species-dependent mass transfer coefficient of slag, industrial validation |
| Harada et al. | 2013 | ChemApp/empirical | Double film theory                  | Stirring-dependent mass transfer coefficient of steel, species diffusion-dependent mass transfer coefficient of slag, detailed |
| Scheller and Shu | 2014 | SimuSage        | Double film theory; tank mixing model | Constant mass transfer coefficient, defined 4 tanks |
| Cicutti et al. | 2015 | Empirical       | Double film theory                    | Species-dependent mass transfer coefficient, inclusion formation consideration |
| Piva et al.  | 2016 | FactSage       | EERZ                                  | Fitting to the laboratory experimental results |
| Van Ende et al. | 2017 | FactSage       | EERZ                                  | Inclusion-type changes, heat input and loss were considered |
| Ren et al.  | 2017 | FactSage       | Tank mixing model                    | Mixing time was estimated, defined 4 tanks |
| Shin et al.  | 2017 | FactSage       | EERZ                                  | Refractory dissolves in slag, fitting to the laboratory experimental results |
| Zhang et al. | 2018 | Empirical       | Double film theory                    | Comprehensive |
| Tabatabaei et al. | 2019 | Empirical       | Double film theory                    | Inclusion transformation kinetics was considered |
| Kumar et al. | 2019 | FactSage       | EERZ                                  | Evaluation of mass transfer and inclusion floating |

The high efficiency,[9–17] as shown in Table 1. 1) Most researchers used commercial software (FactSage, Metsim, ChemApp, and SimuSage) for thermodynamic calculations, whereas the empirical models offer a faster calculation speed.[18] 2) The double film theory was used to describe the reaction kinetics and the EERZ method is simplified from double film theory under the assumption of the same mass transfer coefficient of different species in one phase. 3) Mass transfer coefficients are the most important parameters for the ladle refining model. Tank models were applied to describe the inhomogeneity in the ladle simply, whereas the tank number was set as four.

At the same time, comprehensive models are gaining more importance because each of the metallurgical factors in the refining furnace can affect the steel quality.

The present project aims to develop comprehensive and thorough process models to simulate the secondary refining process, which considers the various operations and metallurgical routes besides the metallurgical phenomenon in the individual metallurgical station. LF (including the tapping process) and Ruhrstahl-Heraeus (RH) models have been constructed and validated through comparing the reported industrial practice. The modeling concept, description, and case study were presented at the 4th European Steel Technology and Application Days (ESTAD) 2019.[19]

In the present study, the detailed description of the LF model was addressed. The LF refining process model was developed based on the tank-in-series model and EERZ method. As applied by Scheller et al. and Ren et al.,[8,12] the tank model was used to simply describe fluid flow and the inhomogeneity of steel in the ladle. The proposed mathematical description of the tank-in-series model of the gas-stirred ladle by Murthy was applied.[20] Compared with the reported four-tank model, the finite number of tanks and the volume of each tank including the plume zone were defined based on the Ar flow rate and LF dimension. The EERZ method suggested by Van Ende et al. was used to describe the kinetics of the steel/slag reaction.[21] The modeling was along the concept of linking a practical metallurgical model to thermodynamic databases. The thermodynamic library—ChemApp—was applied to carry out equilibrium calculations. The steel/slag reaction, lining dissolution, alloy addition, and air absorption were considered. The determination of the tank number was instructed by simulations of the model with varied tanks. The inhomogeneity of the steel and inclusion concentrations in different tanks were displayed. The reasonability of the predicted compositions of steel, slag, and inclusions using the proposed model was illustrated by comparing predictions with the reported industrial measurements.

2. Modeling

In this section, the modeling methods and tools are introduced and then the modeling and calculation process are briefly described.

2.1. Modeling Background

The basic idea behind this work is the coupling of metallurgical models to thermodynamic databases. In the former study, microsegregation and inclusion formation during the cooling and solidification process of steel were simulated using the same concept.[22–25] As shown in Figure 1, different models such as LF, RH, microsegregation, and inclusion formation, which consider process operations, reaction thermodynamics, and kinetics, can be programmed using the FORTRAN language.[23] The thermodynamic library—ChemApp—links the metallurgical models to
The databases are provided by FactSage in the form of a ChemSage file. FactSage, ChemSage, and ChemApp are products of GTT Technologies, Herzogenrath, Germany. In the calculations, the initial conditions and necessary parameters such as time schedule, mass transfer, and diffusion coefficients were inputs into the models. Under the local conditions predicted by the metallurgical models, thermodynamic equilibrium calculations were carried out by ChemApp and its subroutines. After the calculation, the necessary thermodynamic results were obtained and returned to the model for subsequent calculations.

2.2. Modeling Process

The schematic of the proposed model is shown in Figure 2. As shown in Figure 2, the LF refining process contains multiphysical phenomena and multiphase reactions. To consider the mixing phenomenon and inhomogeneity in the ladle metallurgy process in a simple way, the steel bath in the ladle was divided into a finite number \((n+1)\) of tanks, which is the so-called “tank-in-series” model.\(^{[27]}\) The mathematical description of a tank model for a gas-stirred ladle proposed by Murthy was applied in the present work. The nozzle was assumed to be located in the center of the ladle bottom. Hence, all the tanks are centrosymmetric. The volume of each tank in the stirring LF was defined based on the ladle dimensions. The geometry of the plume zone (the \((n+1)\)th tank) was assumed to be a cone. The cone angle \((\theta_c)\) was estimated using Equation (1) and (2), which were empirically summarized from physical simulations.\(^{[28]}\) The volume of the plume zone can be calculated by the cone angle, which varies with the stirring energy. As shown in

![Figure 2. Schematic of the LF process model.](image-url)
Figure 2, tanks 1–n have the same height of $H/n$, so the volume of each tank was calculated after the plume zone was determined, which also changes with the stirring energy. When the volume of the tank was increased, it was assumed that the “newly added” steel and inclusions to the tank were mixed well with the original phases. In the present model, the mass flow direction of steel is assumed as the arrow direction in Figure 2. The plume zone only exchanges with tanks 1 and n, whereas the exchanges with tanks 2–n−1 will be further considered based on the simulations of computational fluid dynamics. The average mass flow rate was calculated by Equation (3)–(5).\(^{[28]}\)

The determination of the tank number will be discussed in a subsequent section.

\[
\frac{\theta_f}{180} = 0.915 Fr_m^{12} \left( \frac{H}{D} \right)^{0.254} \left( \frac{d_n}{D} \right)^{0.444} \tag{1}
\]

\[
Fr_m = \frac{16Q^2}{\pi^2 d_n^2 gH} \left( \frac{\rho_G}{\rho_L \rho_G} \right) \tag{2}
\]

\[
\dot{V}_L = 2.81 \times 10^{-3} \varepsilon^{0.625} H^{0.942} d_n^{1.199} \tag{3}
\]

\[
\dot{\varepsilon} = \varepsilon \rho_L \tag{4}
\]

\[
\varepsilon = \left( \frac{n_c R T}{m_L} \right) \ln \left( \frac{P_t}{P_s} \right) \tag{5}
\]

where $\theta_f$ is the plume cone angle; $Fr_m$ is the modified Froude number as defined in Equation (2); $H$ is the steel bath height; $D$ is the bath diameter; $d_n$ is the diameter of the nozzle; $Q$ is the gas flow rate, $\rho_G$ and $\rho_L$ are the gas and liquid densities, respectively; $\pi$ is the circumference ratio; $g$ is the gravity acceleration; $\dot{V}_L$ is the average steel recirculation rate; $\dot{\varepsilon}$ is the rate of kinetic energy dissipation which can be calculated by Equation (4) and (5); $\varepsilon$ is the effective stirring power per unit steel; $n_c$ is the mole of blowing Ar; $R$ is gas constant; $T$ is the temperature; $m_L$ is the mass of the liquid steel; and $P_t$ and $P_s$ are the gas pressure at the bottom and surface of the ladle, respectively.

As shown in Figure 2, the steel/slag reaction (ES1 and ES2) was assumed to occur at the interface of slag and steel of tanks 1 and $n+1$. The EERZ method was applied to treat steel/slag reaction.\(^{[23]}\) In the method, three zones were defined: bulk steel, bulk slag, and interfacial layer. At each calculation step, the mass of phases ($\Delta m$) participating in the reaction (forming the interfacial layer) which depends on the mass transfer coefficient ($k$) in each phase was calculated using Equation (6). In the present calculation, an empirical stirring energy-dependent mass transfer coefficient of steel ($k_m$ in Equation (7)) was applied.\(^{[14]}\)

The mass transfer coefficient of slag was assumed to be one-tenth of that of steel. Meanwhile, inclusions were assumed to float to the interfacial layer (3 in Figure 2) from each tank at an empirical rate of $r_{fl}$ (Equation (8)).\(^{[20]}\) The phases in the interfacial zone were assumed to approach equilibrium at each calculation step. Afterward, the products of each phase returned to the bulks, respectively, whereas the slag was trapped by the steel at the rate of $r_{fl} \times 10^{-5}$. Inclusions generated in the steel/slag reaction were removed to the bulk slag. In the bulk zones, the phases were also assumed to reach equilibrium state, after which the steel and slag were transported from the bulks to the interface for the next calculation. In the LF treatment process, alloys were assumed to be added into tanks $n/2$ and $n+1$ (plume zone) and to be instantly dissolved. The air absorption was considered by the empirical rate and added for the steel/slag interfacial reaction.

The calculation flow chart of the proposed model is shown in Figure 3. The compositions of steel and slag, time schedule of the treatment, and dimensions of the LF were set as the initial conditions. Before the treatment, steel and slag were assumed to be in the equilibrium state. At each calculation step, inclusions floating and air absorption were first calculated for the interfacial reaction. As mentioned previously, the interfacial reaction was assumed to occur between slag and steel in tanks 1 and $n+1$ ($T_{i}/Sl.$ and $T_{n+1}/Sl.$ in Figure 3). The mass of the steel and slag participating in the interfacial reaction of $T_{i}/Sl.$ and $T_{n+1}/Sl.$ was proportional to the contact area of the tanks and slag. After the
The arcing period was 400 s (from 1580 to 1980s).

Figure 4 means the mixing time, \( t_{\text{mix}} \). The compositions of slag (% mass) shows the chemical compositions from FactPS, CaS from FSstel and MgO, Al\(_2\)O\(_3\), SiO\(_2\), CaO, CaAl\(_2\)O\(_4\), and CaAl\(_{12}\)O\(_{19}\) from FToxid were used to describe the precipitations in the liquid steel and slag. The time step was set as 0.12 s. The air absorption and lining dissolution were not considered in the present calculations.

### 3. Results and Discussion

Using the proposed model, a 165 ton ladle refining process was simulated. The operational data and corresponding measurements of the ladle refining process were reported by Graham and Irons.\(^4\) The initial chemical compositions of the steel and slag are shown in Table 2 and 3.\(^4,5,7\) Figure 4 shows the operational schedule and temperature of the LF refining process.\(^4,5,7\) From Figure 4, it can be found that two Ar blowing strategies were assumed, resulting in the changes of plume zone volume and mass transfer coefficients in the simulation. Alloy additions were performed after 0.12 s (Al) and 1140 s (Al and FeMn). The FeMn alloy is composed of 7%C–78%Mn–15%Fe.\(^7\) The evolution of temperature corresponds to the measured values.\(^7\) The arcing period was 400 s (from 1580 to 1980s). The displayed temperature in Figure 4 was from the measurement and input into the model as boundary condition. In the present calculations, FStel, FToxid, and FactPS database from FactSage 7.2 were selected and applied. The LIQUID phase from FStel was used to describe the liquid steel. The Slag–liquid phase from FToxid was applied to describe the liquid slag and liquid inclusion in the steel. Meanwhile, the following phases: FeO(s) from FactPS, CaS from FStel and MgO, Al\(_2\)O\(_3\), SiO\(_2\), CaO, CaAl\(_2\)O\(_4\), and CaAl\(_{12}\)O\(_{19}\) from FToxid were used to describe the precipitations in the liquid steel and slag. The time step was set as 0.12 s. The air absorption and lining dissolution were not considered in the present calculations.

#### 3.1. Inhomogeneity of the Components

Before comparing the calculated results with the industrial measurements, the determination of the tank number of the proposed model and the inhomogeneity of the components in different tanks were discussed. A few tanks are necessary to describe the mixing phenomenon, whereas the calculation time also needs to be taken into account. To define the proper tank number, the mixing time was selected as a referred parameter due to its empirical availability. Here, the mixing time was defined as the period of bulk mixing degree approaching 0.95. It was suggested that the calculated mixing time increased with the tank number.\(^20\) Therefore, it was assumed that the tank number was adequate as soon as the calculated mixing time from the model was close to the empirical value. The empirical mixing time was calculated using Equation (9).

\[
t_{\text{mix}} = 25.4 \times Q^{-0.33} \times H^{-1} \times R^{2.33}
\]

where \( t_{\text{mix}} \) means the mixing time, \( Q \) is the argon flow rate, \( H \) is the height of the steel bath, and \( R \) is the radius of the LF.

In the calculation, carbon in the steel was selected as the tracer. In the second deoxidation (1140 s), 7% carbon in FeMn alloy was added, which did not react with other solutes. The empirical mixing time with the changing argon flow rate and the calculated ones from the model with different tanks are shown in Figure 5. From Figure 5 a, it is shown that the mixing time is 52.4 s for the local argon flow rate of 0.0138 m\(^3\) s\(^{-1}\) (0.833 m\(^3\) min\(^{-1}\)). In Figure 5b,c, the mixing degree of carbon in the tanks is selectively shown. Note that the calculated mixing time was determined when the mixing degree in all the tanks reached 0.95. Figure 5 d shows the mixing time change with the increasing tank number. It is found that the mixing time increases from 7.05 to 55.09 s with the increasing tank number from 4 to 26. Meanwhile, the necessary calculation time for the simulation of 35 min LF treatment increases from 16 to 60 h with the increasing tank number, which lowers the model efficiency. The calculation was carried out using a normal office PC with two processors. The calculation time should be shortened by the improved hardware and programming techniques. Nevertheless, the mixing time (50.36 s) calculated from the model with 24 tanks is close to the empirical value (52.40 s), so the model with 24 tanks was believed to be suitable and reasonable in the present study.

The inhomogeneity of the concentration of solutes in the steel causes the difference in chemical reactions and inclusion formation. Figure 6 shows the inhomogeneity of the concentrations of aluminum (Al) and alumina (Al\(_2\)O\(_3\)) in different tanks.

### Tables

**Table 2.** The compositions of steel (% mass).

| Steel mass [ton] | Mn  | Si  | Al  | Ca | Mg  | O   | S   |
|------------------|-----|-----|-----|----|-----|-----|-----|
| 165              | 0.12| 0.008| 0.001| 10^-6| 10^-6| 0.01| 0.06|

**Table 3.** The compositions of slag (% mass).

| Slag mass [ton] | MgO | Al\(_2\)O\(_3\) | SiO\(_2\) | CaO | MnO | FeO | CaS |
|-----------------|-----|--------------|----------|-----|-----|-----|-----|
| 4.95            | 8   | 32           | 5.9      | 51.5| 0.8 | 1.9 | 0.01|

### Figure 4

Operational schedule and temperature change of the LF refining process.
As shown in Figure 6a, the concentration of Al in tank 13 soars after the addition of Al due to the assumption of the local dissolution of Al in tank 12, whereas the increases in the other tanks occur at a later stage. In the mixing process, the concentrations of Al in all the tanks have a significant difference, though they tend to be the same by recirculation. The variations of Al content can
lead to different contents of Al$_2$O$_3$ in the tanks, as shown in Figure 6b. For example, at approximately 1143 s, Al concentration in tank 4 is the lowest among the three tanks, whereas tank 4 has the lowest content of Al$_2$O$_3$. In the displayed period, the contents of Al$_2$O$_3$ in different tanks have a general trend: it first increases because of the additions and then decreases due to the assumed inclusion floating. It is found that the concentrations of Al$_2$O$_3$ have a clear difference even after the solutes approach a high mixing degree. In another case, it was suggested that the inclusion types were also possibly varied in different tanks.\textsuperscript{[12]}

### 3.2. Compositions of Steel, Slag, and Inclusions

In this section, the predicted evolutions of steel, slag, and inclusions are discussed and compared with the industrial measurements. The changes in steel and slag compositions during the LF treatment process are shown in Figure 7 and 8.\textsuperscript{[5]} From Figure 7, it can be found that the calculated concentration profiles of Si, Mn, S, and Al agree well with the measured results. After the first deoxidation by Al at the beginning of the LF treatment, the concentrations of Al and S gradually decrease, whereas Mn concentration increases. The changes are mainly caused by the steel/slag reaction: Al in the steel with high activity reduces the MnO from the slag, which is also indicated in Figure 8b. S in the steel is removed to the slag by the reaction with CaO. From 450 to 1140 s, the change in speed of Mn, S, and Al concentrations is significantly reduced due to the lowering Ar flow rate and mass transfer for the reactions. This indicates that the model can react well to the operational change. Before secondary deoxidation at 1140 s, Si concentration changes slightly. The additions of Al and FeMn alloy lead to the sharp increases in Al and Mn concentrations, which is not real because of the existence of a dissolution period. Subsequently, Al concentration decreases and Si concentration increases, which results from the steel/slag reaction. Al in the steel reduces SiO$_2$, MnO, and FeO in the slag during the interfacial reaction, as also shown in Figure 8b. S is continuously removed in the process. The change in speed of Si, Mn, S, and Al concentration is in good agreement with the Ar flow rate.

As shown in Figure 8, the calculated evolutions of slag compositions fit well with the industrial data. From Figure 8a, Al$_2$O$_3$ content in the slag gradually increases due to the steel/slag reaction and inclusion floating, whereas CaO content decreases. MgO content in the process changes slightly. In Figure 8b, as stated earlier, SiO$_2$, MnO, and FeO are reduced by Al during the interfacial reaction. The FeO content measured is a little higher than the predicted value, which is attributed to the oxygen entrapment from the air and the oxidation reaction.

Figure 9 shows the evolution of overall inclusion compositions and inclusion phases during the LF treatment process.\textsuperscript{[5]} In Figure 9a, it is found that Al$_2$O$_3$ generated by deoxidation is the dominant component, whose percentage is in a decreasing trend due to floating and the steel/slag reaction. CaO and MgO contents gradually increase, which results from the steel/slag reaction and slag entrapment. The predicted CaO
and MgO contents are higher than the measured value, whereas the calculated Al$_2$O$_3$ content is lower. The discrepancies become more obvious after second deoxidation. It can be explained by three possible reasons: 1) only a part of Al$_2$O$_3$ participated the steel/inclusion equilibrium and the inclusion transformation rate is slow; 2) the inclusion removal rate is slower at the late stage of LF treatment because the residual inclusions are smaller and not favorable to float up; and 3) the lining dissolution affects the inclusion formation because the inclusion mass is limited at the late stage, which is not considered in the simulation due to a lack of information. As shown in Figure 9b, there are two types of inclusion in the refining process: Al$_2$O$_3$ and slag. The content of Al$_2$O$_3$ in the steel is gradually decreased due to floating and modifying to slag type inclusion through steel/slag reaction. Slag is a liquid solution phase and its main components are Al$_2$O$_3$, CaO, and MgO. As mentioned earlier, this slag type inclusion is the modified product of Al$_2$O$_3$. At the end of the refining, slag is the only type of inclusion in the steel with a content of 23 ppm. As a whole, the predicted evolution of steel, slag, and inclusion compositions during the LF treatment is reasonable and satisfactory when compared with the industrial measurements.

4. Conclusions

In the present work, a LF refining process model was proposed based on the coupling between a tank-in-series model and the “EERZ” method. The proposed mathematical description of the tank-in-series model of gas-stirred ladle by Murthy was applied to consider the steel flow. The thermodynamic library ChemApp was applied to link the source code to thermodynamic databases. In the modeling process, the tank number was determined by comparing the calculated mixing time with the empirical value. The volume of each tank was determined by the dimension of the LF and tank number, which varied with the argon (Ar) flow rate. The steel/slag reaction, lining dissolution, alloy addition, and air absorption could be considered. The stirring energy-dependent mass transfer coefficient and inclusion floating rate were applied in the calculation. Using the model, an industrial LF treatment process was simulated according to data from literature. 1) By defining the number of tanks, the mixing time and inhomogeneity of the components were studied. 2) The validity of the model was illustrated by the reasonable agreement of the predicted evolution of steel, slag, and inclusion compositions and the measured results.

While there is no significant improvement in the predicted compositions of steel, slag, and inclusions compared with the measurements and other simulations in the present case study, the present modeling work exhibits huge potential. In future work, the inhomogeneity in different tanks will be further addressed by considering the local conditions, e.g., inclusion removal, lining dissolution, and transient phenomena. With the flexible model structure, the model is promising to investigate the refining process and mixing phenomenon of a noncentral-symmetric system based on the simulation of computational fluid dynamics.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

ladle refining, mixing, modeling, steels, thermodynamics
[1] J. Peter, K. D. Peasley, D. G. C. Robertson, M. Hall, B. G. Thomas, in Proc. AISTech 2005, Vol. 1, Association for Iron & Steel Technology, Warrendale, PA 2005, p. 959.
[2] METSIM, https://metsim.com/ (accessed: November 2019).
[3] FactSage, http://www.factsage.com/ (accessed: November 2019).
[4] K. J. Graham, G. A. Irons, in Proc. AISTech 2008, Vol. 1, Association for Iron & Steel Technology, Warrendale, PA 2008, p. 1181.
[5] A. Harada, N. Maruoka, H. Shibata, S. Kitamura, ISIJ Int. 2013, 53, 2110.
[6] S. Petersen, K. Hack, P. Monheim, U. Pickartz, Int. J. Mater. Res. 2007, 98, 946.
[7] M.-A. V. Ende, I.-H. Jung, Metall. Mater. Trans. B 2017, 48, 28.
[8] P. R. Scheller, Q. Shu, Steel Res. Int. 2014, 85, 1310.
[9] A. N. Conejo, F. R. Lara, M. Macias-Hernandez, R. D. Morales, Steel Res. Int. 2007, 78, 141.
[10] C. Cicutti, C. Capurro, G. Cerrutti, in 9th Int. Conf. on Clean Steel, Hungarian Mining and Metallurgical Society (OMBKE), Budapest 2015.
[11] S. P. T. Piva, D. Kumar, P. C. Pistorius, Metall. Mater. Trans. B 2017, 48, 37.
[12] Y. Ren, L. Zhang, Ironmak. Steelmak. 2018, 45, 585.
[13] J. H. Shin, Y. Chung, J. H. Park, Metall. Mater. Trans. B 2017, 48, 16.
[14] Y. Zhang, Y. Ren, L. Zhang, Metall. Res. Technol. 2018, 115, 415.
[15] Y. Tabatabaei, K. S. Coley, G. A. Irons, S. Sun, Steel Res. Int., 2019, 90, 1900155.
[16] D. Kumar, K. C. Ahlborg, P. C. Pistorius, Metall. Mater. Trans. B 2019, 50, 2163.
[17] T. Kargul, J. Falkus, Steel Res. Int. 2010, 81, 953.
[18] Simusage, https://gtt-technologies.de/software/simusage/ (accessed: November 2019).
[19] D. You, S. K. Michelic, C. Bernhard, in METEC @ 4th ESTAD, The Steel Institute VDEh, Düsseldorf, Germany 2019.
[20] G. G. Murthy Krishna, ISIJ Int. 1989, 29, 49.
[21] A. Van Ende, Y. M. Kim, M. K. Cho, J. H. Choi, I. H. Jung, Metall. Mater. Trans. B 2011, 42, 477.
[22] D. You, C. Bernhard, G. Wieser, S. Michelic, Steel Res. Int. 2016, 87, 840.
[23] D. You, S. K. Michelic, C. Bernhard, D. Loder, G. Wieser, ISIJ Int. 2016, 56, 1770.
[24] D. You, S. K. Michelic, G. Wieser, C. Bernhard, J. Mater. Sci. 2017, 52, 1797.
[25] D. You, S. K. Michelic, C. Bernhard, Metals 2018, 8, 2075.
[26] S. Petersen, K. Hack, Int. J. Mater. Res. 2007, 98, 935.
[27] O. Levenspiel, Chemical Reaction Engineering, Wiley, New York, NY, 1972.
[28] G. G. Krishna Murthy, A. Ghosh, S. P. Mehrotra, Metall. Trans. B 1989, 20, 53.
[29] K. J. Graham, G. A. Irons, in Proc. AISTech 2009, Vol. 1, Association for Iron & Steel Technology, Warrendale, PA 2009, p. 1003.
[30] D. Mazumdar, S. Das, S. Bajpayee, ISIJ Int. 1997, 37, 194.