Segregation of a Phosphorus Rich Phase During Differential Solidification of BOF Slag

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This study investigated the segregation behaviour of the phosphorus rich (P-rich) phase from the iron-rich (Fe-rich) phase in steelmaking slag from laboratory to industrial scale using computational fluid dynamics (CFD) in order to propose a suitable separation practice for the P-rich phase. Crucible experiments and corresponding CFD simulations using enthalpy-porosity approach were first performed to verify the concentration difference of phosphorus in the two phases. Both simulation and experimental results showed ~ 17 to 18 pct increase in phosphorus concentration in the top region of the crucible after solidification. The simulations were then scaled up to an industrial slag pot and slag pit. Reasonable agreement was obtained with published results for phosphorus concentration, and the total liquid amount in the 16-tonne slag pot, under practical cooling conditions. Simulations in the 30-tonne slag pit with in-ground insulation showed an increase of ~ 25 pct of the P-rich phase in the top region (while concentrating the Fe-rich phase in the bottom region). Differential concentration of the P-rich phase within the slag (as a result of heat transfer, micro/macro-segregation) suggested that separation of phosphorus in industrial scale slag pot and slag pit—as batch systems—is possible. Suggestions for separation in continuous operation are also discussed.

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I. INTRODUCTION

STEELMAKING slag is a significant by-product from the basic oxygen furnace (BOF) steelmaking process, with typically between 100 and 120 kg produced for one tonne of steel in conventional steel plants. While more than 80 pct of the steel slag was utilised for cementitious products, concrete, road construction and fertiliser in Europe, United States and Japan, only about 30 pct of the steel slag was utilised in China. [1] Due to the high lime and iron content, steelmaking slag has historically been recycled into the sintering or steelmaking process thereby reducing cost and CO₂ emissions by replacing raw fluxes, however, the amount of recycling is limited by the slag’s high phosphorus (P) content. Conversely, the high-P slag can be a source of fertiliser or soil nutrient, particularly if enriched P content.[1] Utilising steelmaking slag for soil improvement would help ease global concerns about the long-term access to sufficient phosphorus for food production.[13] Together with the globally increasing demand for steel products, these facts mean that an opportunity exists to separate the P from the iron in steelmaking slag leading to both environmental and economic benefits, if a suitable separation process can be developed.

The main phases in steelmaking slags are a P-rich, dicalcium silicate–tricalcium phosphate (C2S–C3P) phase, and a Fe-rich, CaO–SiO₂–Fe₂O₃-based phase with MgO, MnO, free CaO and wustite.[3,4] The conventional technique of magnetic separation of the Fe-rich phase involves the high energy cost of grinding.[5–8] Acid leaching for removing the P-rich phase[9–11] requires energy intensive conditions such as crushing/grinding and low cooling rate presenting economical restrictions to its industrial application. Separation due to gravity by floating of the C₂S–C₃P crystals was shown possible under a low cooling rate of below 2 °C/m[8,12–14] which could only be implemented under controlled cooling. Ideally separation should be undertaken whilst the slag is in the liquid state so that crushing or grinding are not be required. As noted, P is known to preferentially
partition to the $C_2S$–$C_3P$ solid solution phase, leaving behind a Fe-rich phase. Also, $C_2S$–$C_3P$ is known to solidify first during cooling, due to its relatively high liquidus temperature compared to the Fe-rich matrix. This difference in solidification behaviour indicates P removal from the slag is possible providing the $C_2S$–$C_3P$ phase can be separated from the rest of the slag.

While solidification for other binary metal alloys such as lead/tin, copper/nickel or copper/zinc are well studied, to the best of the author’s knowledge, there is no such solidification model for steelmaking slag. This study aims to understand the solidification and separation feasibility of the steelmaking slag for an industrial scale. Performing experiments is very difficult for such a high temperature and complex system, therefore, a small-scale crucible test was carried out for model validation prior to performing the large-scale simulations. The aims of this paper are summarised as follows:

- To investigate the solidification and segregation behaviour of the two main phases present in BOF slag, P- and Fe-rich phases, using numerical modelling validated with experimental data at crucible-scale;
- To apply the validated solidification models for an industrial scale (e.g. slag pot, slag pit);
- To explore the potential geometries for separation of the above two enriched material streams at an industrial scale.

II. CFD MODELLING

A. Background of the Enthalpy-Porosity Solidification Model

Slags solidify over a temperature range, and a mushy zone exists between the liquidus and solidus temperature which consists of both solid and liquid phases. Numerical modelling of solidification in such system couples several mathematical solvers such as fluid flow of the molten phase, heat transfer, phase change phenomenon, and the transport of species between phases. A comprehensive review of numerical modelling in such systems can be seen in Verma and Dewan. The main challenge of the numerical scheme was to trace the moving solid-liquid interface coupled with the enthalpy variation during the phase transformation. Moving grids required in such a complex solver is computationally intensive. One way to overcome this challenge is to simplify the system to a one phase problem using the enthalpy-porosity technique proposed by Voller et al. In this well-known numerical scheme, a porous medium is employed so there is no need to explicitly track the melt interface, but a ‘liquid fraction’ is calculated instead, based on an enthalpy balance. In the mushy zone, the liquid fraction defines porosity which decreases from one to zero as the material solidifies. When the porosity reduces to zero (fully solidified), the velocity turns to zero, which is the key point of the porous approach. Specifically in the mathematical scheme, temperature dependent enthalpy is added as a source term in the energy equation, whereas a permeability source term is added in the momentum equation, which accounts for switching the velocity to zero at a fully solid state. This technique has been incorporated in the solidification model by Ansys Fluent version 2020 R2. The following sections discuss how the simulations are implemented.

B. Geometry and Mesh

The present study investigated the cooling, solidification and segregation behaviour of the BOF slag at two different scales: laboratory scale with controlled cooling rates, and an industrial scale with practical cooling conditions. Figure 1 shows schematic diagrams of slag cooling in platinum crucible (a), slag pot (b) and slag pit (c) geometries. Detailed dimensions are shown in Table 1.

C. Governing Equations

A single phase CFD model was developed comprising a binary species system with solidification sub-model coupled with energy balance. The slag was assumed to have two major components: the solid solution phase with a majority of the phosphorus content ($P$-rich phase), and the liquid matrix with a majority of iron content (Fe-rich phase).

In the mushy zone constrained by the liquidus and solidus boundary, as solidification proceeds, the solutes are rejected to the melt as solubility is usually lower in the crystalline state than in the melt. Diffusion processes take place to redistribute the rejected solutes, which causes micro-segregation. The internal convective flows driven by temperature and composition difference (thermal/solutal flows) enable the circulation of the solutes, which leads to macro-segregation. To investigate the solidification behaviour, the thermophysical properties (i.e. density, viscosity, heat capacity, thermal conductivity) as well as the thermodynamic behaviour such as liquidus/solidus/eutectic temperatures, liquidus slope, partition/diffusion/thermal/solutal-expansion coefficients of the eutectic system are to be specified. Governing equations are given below.

The continuity equation is given as

$$\frac{\partial (\rho)}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad [1]$$

The momentum conservation equation can be described as

$$\frac{\partial (\rho \vec{v})}{\partial t} + \rho \vec{v} \cdot \nabla \vec{v} = -\nabla p + \mu \nabla \cdot \nabla \vec{v} + \frac{1}{3} \mu \nabla (\nabla \cdot \vec{v}) + \rho g + S \quad [2]$$

The momentum sink resulting from the reduced porosity in the mushy zone is given as

$$S = \frac{(1 - \beta)^2}{(\beta + \epsilon)} A_{mush} (\bar{v} - \bar{v}_p) \quad [3]$$
where $\beta$ is the liquid volume fraction, $\varepsilon$ is a small number of about 0.001 to prevent division by zero, $A_{\text{mush}}$ is the mushy zone constant, and $v_p$ is the solid pulling velocity due to the pulling of solidified material out of the domain, which is assumed zero in this study.

As discussed, the enthalpy-porosity technique treats the mushy zone as a porous medium. The porosity in each cell is set equal to the liquid fraction of that cell. For fully solid cells, the porosity is zero which means zero velocity in this region. When the liquid solidifies in the mushy zone, solutes diffuse from the solid phase into the liquid phase. This effect is quantified by the partition (segregation) coefficient $K_i$ of solute $i$ which is the ratio of the mass fraction in the solid to that in the liquid at the interface, following the Scheil approximation [17] used in this study.

For solidification model, the energy equation is given as

$$
\frac{\partial \rho H}{\partial t} + \nabla \cdot (\rho \mathbf{v} H) = \nabla \cdot (k \nabla T)
$$

where $H$ is the enthalpy of the material which is the sum of the sensible enthalpy $h$ and the latent heat $\nabla H$

$$
H = h + \nabla H
$$

where $h = h_{\text{ref}} + \int_{T_{\text{ref}}}^{T} c_p dT$

$$
\nabla H = \beta L
$$

and

$$
\beta = \left( \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} \right)^q
$$

where $\beta = 0$ if $T \leq T_{\text{solidus}}$; $\beta = 1$ if $T > T_{\text{liquidus}}$.

The liquid fraction was computed using power laws for multicomponent systems, as shown in Eq. [8]. A $q$ value of approximately 2 was used (in Fluent) for binary mixtures depending on the micro-segregation models. Mixing laws were used to update the liquidus and solidus temperature, $L$ is the latent heat which can vary between zero for solid and $L$ for liquid.

The solidus and liquidus temperatures of the mixture are obtained from linear interpolations from the liquidus line shown in the phase diagram (using Scheil model), which are given as

$$
T_{\text{solidus}} = T_{\text{melt}} + \sum_{\text{solutes}} \frac{m_i Y_i}{K_i}
$$

$$
T_{\text{liquidus}} = T_{\text{melt}} + \sum_{\text{solutes}} m_i Y_i
$$

where $Y_i$ is the mass fraction of solute $i$ and $m_i$ is the slope of the liquidus surface with respect to $Y_i$. There are only two species in the mixture, so the first species material of the mixture is the solute and the last species is the solvent. The liquidus slope of species $m_i$ is calculated from the Eutectic temperature and the Eutectic mass fraction as,

$$
m_i = \frac{T_{\text{Eut}} - T_{\text{melt}}}{Y_{i,\text{Eut}}}
$$

Updating the liquid fraction ($\beta$) via Eq. [8] can cause numerical errors and convergence difficulties in multi-component mixtures. Instead, the liquid fraction is updated as,

$$
\beta^{n+1} = \beta^n - \frac{\lambda}{\rho V L - \alpha_p \Delta t L \frac{\partial T}{\partial T^*}}
$$

where $n$ is the iteration number, $\lambda$ is a relaxation factor with a default value of 0.9, $\alpha_p$ is the cell matrix coefficient, $\Delta t$ is the time step, $\rho$ is the current density, $V$ is the cell volume, $T$ is the current cell temperature, and $T^*$ is the interface temperature.

In this study, Scheil model [17] was selected (i.e. solidification occurs within a finite time), where zero diffusion in the solid and infinite diffusion in the liquid is assumed (i.e. the solute concentration is uniform in the liquid while it has a profile in the solid), and

Fig. 1—Schematic sketches of different geometries. (a) Platinum crucible, $D = 5$ mm. (b) Slag pot, $V = 5.1$ m$^3$. (c) Slag pit, $V = 10$ m$^3$. 

equilibrium is reached at the interface between liquid and solid. The following formulations apply for the Scheil model.

\[
T = \frac{T_{melt} - (T_{melt} - T_{liquidus})^P}{P^P - 1}
\]

where

\[
P = \frac{T_{melt} - T_{liquidus}}{T_{melt} - T_{solidus}}
\]

The species equation is given as

\[
\frac{\partial}{\partial t} (\rho Y_{i,\text{liq}}) + \nabla \cdot (\rho \beta \vec{v}_{\text{liq}} Y_{i,\text{liq}}) = \nabla \cdot (\rho \beta D_i \nabla Y_{i,\text{liq}}) - K_i \frac{\partial}{\partial t} (\rho(1 - \beta)) + \frac{\partial}{\partial t} (\rho(1 - \beta))
\]

where \(\vec{v}_{\text{liq}}\) is the velocity of the liquid which is given as

\[
\vec{v}_{\text{liq}} = \frac{\vec{v}}{\beta}
\]

where velocity \(\vec{v}\) is computed from the momentum equation.

\(D_i\) is the mass diffusion coefficient. The liquid mass fraction \(Y_{i,\text{liq}}\) and solid mass fraction \(Y_{i,\text{sol}}\) of species \(i\) are related to each other by the partition coefficient \(K_i\) which is required as an input obtained from the phase diagram.

\[
Y_{i,\text{sol}} = K_i Y_{i,\text{liq}}
\]

It is worth noting that, for the convective flows driven by thermsolutal effects, the Boussinesq model is applied for faster convergence compared with the use of fluid density as a function of temperature. This model treats density as a constant value in all solved equations, except for the buoyancy term in the momentum equation, i.e., Eq. [2]. The term appearing in the momentum equation is replaced by

\[
\rho g \approx \rho_c g (\tau(T - T_e) + c (Y_{i,\text{liq}} - Y_e))
\]

where \(\rho_c\) and \(T_e\) is the reference density and temperature, which was defined at the eutectic reaction in this study. \(\tau\) and \(c\) is the thermal expansion and thermal solutal coefficient, respectively. Within the liquid phase (molten slag) the term \(\tau(T - T_e) \ll 1\) is required by this Boussinesq approximation.

| Scale            | Dimensions                  | Wall Thickness | Capacity Estimate | Modelling | Experiment |
|------------------|-----------------------------|----------------|-------------------|-----------|------------|
| Pt Crucible      | \(D = 5\) mm, \(H = 4.3\) mm | 0.1 mm         | 150 mg            | yes       | yes        |
|                  |                             |                | \(7.77 \times 10^{-8}\) m³ |           |            |
| Slag Pot         | \(D_1 = 1.6\) m, \(D_2 = 2\) m, \(H = 2\) m | 0.12 m         | 16 t/5.1 m³       | yes       | published data [8] |
| Slag Pit         | \(L = 4\) m, \(W = 2.5\) m, \(H = 1\) m | 0.12 m         | 30 t/10 m³        | yes       | no         |

**Table I. Laboratory and Industrial Scales Used**

![Fig. 2—Temperature profile during heating and cooling in the crucible: controlled heating-holding stage ABC, controlled cooling stage CDE, and natural cooling stage EF (only stage CDE and EF were applied in the simulations).](image)

**D. Input Parameters**

1. **Boundary and other conditions**

   Evaluations were first carried out to obtain suitable time step, mesh size, and appropriate residuals for the above governing equations. The residuals were observed to start flattening out after 50 iterations; hence, this number was set as the number of iterations required for each time step. A mass balance was verified for each of the two species using these configurations. The satisfied scaled residual was found to be \(10^{-7}\) for continuity and momentum equations, and \(10^{-10}\) for energy and species transport equations. The simulations were run on a high performance computer: \(32 \times 5\) 12 GB nodes powered by 2.7 GHz Intel Xeon Gold (E5-6150) processor. The initial conditions include temperature at 1873 K and a secondary concentration of the solute at 40 pct.

   For the small Pt crucible, different cooling stages were applied (to promote the positive segregation of the P-rich and Fe-rich phases) to match the experimental procedure. Figure 2 shows the temperature profile for both heating-holding (ABC) and cooling (CEDF) stages. However, only the cooling stages (CDEF) were implemented in the simulation while heating and holding (homogenising) stages were not required. This is because the homogeneous temperature can be obtained by initializing the simulation at the first step.
The cooling was controlled at a slow cooling rate of 10 K/min in the first 15 minutes, from 1873 K (stage $C$) to 1723 K (stage $D$). It was held at this temperature until homogeneous temperature was achieved (stage $E$). After that the crucible was cooled in air (stage $F$). Temperature profile was set as the boundary conditions during stage $CDE$ while heat transfer coefficients were required for the “mixed” boundary conditions during stage $EF$.

Table II. Boundary Conditions, Mesh Information, and Time Step for Three Cases Studied

| Scale                        | Side wall                                      | Bottom                                         | Top                                            | Other conditions                          |
|------------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------------------------|--------------------------------------------|
| Pt Crucible                  | • mixed BC for Wall                            | • mixed BC for Wall                            | • mixed BC for Wall                            | • mesh: 13000 cells                       |
|                              | • wall: 0.1 mm platinum                       | • Wall: 0.1 mm Pt & 5 mm $\text{Al}_2\text{O}_3$| • Wall: 0.1 mm Pt & 5 mm $\text{Al}_2\text{O}_3$| • most hexahedral cells                   |
|                              | • natural convection for vertical cylinder & radiation. | • natural convection for flat surface & radiation. | • zero thickness                               | • time step: 10 ms                        |
|                              | EF stage:                                      | EF stage:                                      | EF stage:                                      | • actual time: ~ 15 days                   |
|                              | • mixed BC for Wall                            | • mixed BC for Wall                            | • Mixed BC for Wall                            |                                            |
|                              | wall: 0.1 mm platinum                         | Wall: 0.1 mm Pt & 5 mm $\text{Al}_2\text{O}_3$| Wall: 0.1 mm Pt & 5 mm $\text{Al}_2\text{O}_3$|                                            |
|                              | • natural convection for vertical cylinder & radiation. | • natural convection for flat surface & radiation. | • Natural convection for flat surface & radiation |                                            |
|                              | EF stage:                                      | EF stage:                                      | EF stage:                                      |                                            |
|                              | • mixed BC for Wall                            | • mixed BC for Wall                            | • mixed BC for wall                            | • mesh: 44736 cells                       |
|                              | • wall: 120 mm cast-iron                      | • Wall: 320 mm cast-iron (*)                   | • Wall: 120 mm cast-iron (*)                   | • most hexahedral cells                   |
|                              | • mixed BC for wall                            | • mixed BC for wall                            | • Mixed BC for Wall                            | • time step: 200 ms                       |
|                              | • natural convection for vertical cylinder & radiation. | • natural convection for flat surface & radiation. | • Natural convection for flat surface & radiation | • actual time: ~40 days                   |
|                              | EF stage:                                      | EF stage:                                      | EF stage:                                      | • actual time: ~15 days                   |
|                              | • mixed BC for wall                            | • mixed BC for wall                            | • mixed BC for wall                            | • mesh: 157,000 cells                     |
|                              | • natural convection for vertical cylinder & radiation. | • mixed BC for wall                            | • mixed BC for wall                            | • most hexahedral cells                   |
|                              | EF stage:                                      | • mixed BC for wall                            | • mixed BC for wall                            | • time step: 100 ms                       |
|                              | • wall: 120 mm cast-iron                      | • Wall: 320 mm cast-iron (*)                   | • Wall: 320 mm cast-iron (*)                   | • actual time: ~50 days                   |
|                              | • mixed BC for wall                            | • mixed BC for wall                            | • Mixed BC for Wall                            |                                            |
|                              | • natural convection for vertical cylinder & radiation. | • mixed BC for wall                            | • Natural convection for flat surface & radiation |                                            |
|                              | EF stage:                                      | EF stage:                                      | EF stage:                                      |                                            |
|                              | • mixed BC for wall                            | • mixed BC for wall                            | • mixed BC for wall                            |                                            |
|                              | • wall: 120 mm cast-iron                      | • wall: 120 mm cast-iron (*)                   | • wall: 120 mm cast-iron (*)                   |                                            |
|                              | • natural convection for vertical cylinder & radiation. | • natural convection for flat surface & radiation. | • natural convection for flat surface & radiation |                                            |
|                              | EF stage:                                      | EF stage:                                      | EF stage:                                      |                                            |
|                              | • mixed BC for wall                            | • mixed BC for wall                            | • mixed BC for wall                            |                                            |
|                              | • wall: 120 mm cast-iron                      | • Wall: 320 mm cast-iron (*)                   | • Wall: 320 mm cast-iron (*)                   |                                            |
|                              | • natural convection for vertical cylinder & radiation. | • natural convection for flat surface & radiation. | • natural convection for flat surface & radiation |                                            |
|                              | EF stage:                                      | EF stage:                                      | EF stage:                                      |                                            |
|                              | • mixed BC for wall                            | • mixed BC for wall                            | • mixed BC for wall                            |                                            |
|                              | • wall: 120 mm cast-iron                      | • Wall: 320 mm cast-iron (*)                   | • Wall: 320 mm cast-iron (*)                   |                                            |
|                              | • natural convection for vertical cylinder & radiation. | • natural convection for flat surface & radiation. | • natural convection for flat surface & radiation |                                            |
| Slag Pot                     | • constant heat flux of 1000 W/m²              | • constant heat flux of 1000 W/m²              | • constant heat flux of 1000 W/m²              |                                            |
| (combined thermal resistance between wall and crust). | (combined thermal resistance between wall and crust). | (combined thermal resistance between wall and crust). | (combined thermal resistance between wall and crust). |                                            |

*320 mm was combined from 120mm of the wall and 200mm of the plate (cast-iron) placed under the slag pot.

**Another study was carried out with no lid which found no real difference in average cooling rate, as discussed in Section IV–B–1.

Table III. Physical Properties of the Slag Mixture

| Parameters                      | Unit    | Values/Rule                           | References/Notes                      |
|---------------------------------|---------|---------------------------------------|---------------------------------------|
| Viscosity, $\mu$                | Pa.s    | $\mu = A = 2.01 \times 10^9 e^{-0.0116 T}$ by Ref. 12, and above discussion | |
| Mass Diffusivity, $D$           | m²/s    | 1.83 x 10⁻⁹                           | Ukyo and Goto [19]                    |
| Specific Heat, $C_p$            | J/kg K  | 1000                                  | [12]                                  |
| Mushy Zone Constant, $A_{mush}$ | kg/s m³ | 10⁶                                   | calculated; compared with [20]        |
| Boussinesq Reference Density,   | kg/m³   | 3058                                  | calculated                           |
| Thermal Expansion Coefficient,  | 1/K     | 1.1 x 10⁻⁴                           | [19]                                  |
| $\sigma_T$                      |         |                                      |                                       |
| Solutal Expansion Coefficient,  | 2.7 x 10⁻³ |                                      | calculated                            |
| $\sigma_C$                      |         |                                      |                                       |
| Eutectic Temperature, $T_e$     | K       | 1436                                  | MTData                                |
| Eutectic Mass Fraction, $Y_e$   |         | 0.93                                  |                                       |
| Partition Coefficient           |         | 0.1                                   |                                       |
| Melting Temperature of the Pure Solvent | K | 2403                                  | [21]                                  |
| Latent Heat of Solidification,  | J/kg    | 235,000                               | [12]                                  |
| $L$                             |         |                                       |                                       |
| Thermal Conductivity, $k$       | W/m K   | 2                                     | [12]                                  |
| Slag                            |         |                                       |                                       |
| Platinum                       | 71.6    | UK Omega website                      |                                       |
| Alumina                        | 26      | Goodellow USA                         |                                       |
| Cast iron                      | 25      | [12]                                  |                                       |
| Emissivity, $\varepsilon$       |         |                                       |                                       |
| Oxidised Platinum              | 0.1     | UK omega website                      |                                       |
| Oxidised Aluminium             | 0.11    | fluke USA website                     |                                       |
| Oxidised Cast iron             | 0.9     |                                       |                                       |
Detailed discussion of (a) the temperature profile is presented in Section 3, and (b) boundary conditions (BC), mesh information and time step for the crucible, slat pot and slag pit are in Table II.

Heat transfer coefficients were calculated and applied to the boundary conditions. Detail formulations are given below.

The convective heat transfer coefficient for flat surface used at the top interface is given as

\[ Nu_{\text{top}} = 0.54Ra_{d_g}^{1/4} \]  \[ (19) \]

\[ h_{\text{top}} = \frac{Nu_{\text{top}}k_g}{d_{cr}} \]  \[ (20) \]

For the side wall, the heat transfer coefficient was calculated using the correlation for natural convection for a vertical cylinder, given as:

\[ Nu_w = 0.68 + \frac{0.67Ra_{d_g}^{1/4}}{1 + (0.49/Pr_g)^{9/16}}^{4/9} \]  \[ (21) \]

\[ h_w = \frac{Nu_wk_g}{d_{cr}} \]  \[ (22) \]

In the above equations, \( Nu \) is Nusselt number, \( Ra_{d_g} \) is Rayleigh number of the gas phase, \( Ra_g = Gr_g\cdot Pr_g \), where \( Gr_g = g\beta(T - T_a)d_{cr}^3/\nu_g^2 \) and \( Pr_g = C_{p,g}\nu_g/k_g \) are the Grashof and Prandtl numbers for air, respectively; \( d_{cr} \) is the internal diameter of the crucible (\( d_{cr} = 4.8\text{mm} \)); \( C_{p,g},\nu_g \) and \( k_g \) are the heat capacity, kinematic viscosity, and thermal conductivity of the gas phase, respectively. The temperature dependency of these values was evaluated at the gas-film temperature \([18]\) using the one third rule as given as:

\[ T_g = T_a + (T_w - T_a)/3 \]  \[ (23) \]

where \( T_w \) is temperature at the outer wall (reduces during cooling) and \( T_a \) is temperature of the air at the far field.

For the bottom wall, the slag pot was assumed to place onto an alumina slab during cooling. A combined thermal conductivity for the two layers used for the bottom wall is given as

\[ k_b = \frac{1}{\frac{\delta}{k_{\text{slab}}} + \frac{\delta}{k_{\text{pt}}}} \]  \[ (24) \]

where \( \delta \) is thickness and \( k_b \) is thermal conductivity of the bottom wall, Pt for Platinum wall and Al₂O₃ for alumina slab (5 mm thickness).

2. Physical properties of the slag

In the CFD model all thermophysical properties were computed as a function of temperature. Details of the properties are presented in Table III.
the present study assumed that the slag is comprised two major phases, viz. phosphorus rich (P-rich) phase and iron-rich (Fe-rich) phase. This simplification is important for the solidification simulations discussed in the next section. Two component phase diagram of \(2\text{CaO} \cdot \text{SiO}_2\) and \(2\text{FeO} \cdot \text{SiO}_2\) have been proposed in literature including the review of Hidayat et al. There is sufficient confidence about the liquidus temperatures of these two phases, \(2\text{CaO} \cdot \text{SiO}_2\) and \(2\text{FeO} \cdot \text{SiO}_2\). However, it is still necessary to redraw a linear binary eutectic diagram presenting a liquidus slope and a single eutectic point, which is required for the solidification model used. This means that a simple linear version of the binary diagram is required.

From the above initial compositions, a mass balance was calculated showing approximately 60 pct of the P-rich phase and 40 pct of the Fe-rich phase. The melting temperatures of the P- and Fe-rich phases were 2403 K and 1478 K (2130 °C and 1205 °C), respectively. The liquidus temperature for a slag with 40 pct Fe-rich phase is 1989 K (i.e. point (2) in Figure 3) obtained from MTData, which is a commercial thermodynamic software package developed at the National Physical Laboratory in the United Kingdom. From these known data points which are presented from points (1) to (5), a linear pseudo binary eutectic phase diagram was drawn as shown in Figure 3. The calculated liquidus temperature from MTData (point ‘2’) was found consistent with the phase diagram reported elsewhere. This diagram is necessary for the simulations as described in Section 3.

It is worth noting that the present phase diagram derived in Figure 3 can be only used for the BOF slags with similar composition compared with one used in this study (i.e. wt pct: 40 CaO, 30 Fe\(_2\)O\(_3\), 30 SiO\(_2\)). Any significant change of the above composition may cause considerable variation in the physical and thermodynamic properties of the slag.

### III. CRUCIBLE EXPERIMENT

Experiments in a small-scale crucible are an essential first step and provide a practical set of results for model validation before performing larger scale simulations. In this study, experiments were carried out with synthetic slag containing (wt pct) 40 CaO, 30 Fe\(_2\)O\(_3\), 5.7 P\(_2\)O\(_5\), and the rest of SiO\(_2\) contained in a 5 mm diameter Pt crucible with a wall thickness of 0.5 mm. The temperature profile at different heating/cooling stages including both controlled and natural cooling was described in the modelling section (Figure 2). First, the slag at stage A was heated up to 1073 K, held for 2 minutes to allow drying and dehydration, and heating up to 1873 K (stage B) at a heating rate of 10 K/min, held at 1873 K for 60 minutes to homogenise the slag (stage C). It was then cooled at the same rate of 10 K/min to a separation temperature of 1723 K (stage CD), held at this temperature for 60 minutes (stage DE), then removed from the furnace and cooled to rm temperature in air (stage EF). The cold sample was sectioned, polished and prepared for SEM and energy dispersive X-ray spectroscopy (EDS) analysis. Solidification and segregation behaviour of the two main streams, i.e. P-rich and Fe-rich phases were analysed using the above techniques; the results were compared with the model predictions.

### IV. RESULTS AND DISCUSSION

#### A. Solidification in a 5 mm Diameter Platinum Crucible

1. **Simulation results**

The simulation commenced at an initial temperature of 1873 K, with a concentration of 40 wt pct of the iron-rich phase. The following sections show temperature distributions, velocity, mass fraction and species concentration at different sequences, from stage ‘C’ to ‘F’, as depicted in Figure 2.
The solution for temperature distribution is obtained from the energy equation Eq. (4) coupled with solutions from Eqs. [1] through [24]. The cooling was controlled in the first two cooling stages CD and DE, and then cooled naturally in air for stage EF. Figures 4(a) and (b) shows the temperature distribution at stages D and F, respectively. At stage D, temperature is slightly higher at the centre of the crucible by approximately 0.5 K. This small discrepancy in temperature is due to the slow cooling CD stage at 10 K/min (which takes 900 s (15 minutes) to reduce the temperature from 1873 K at C to 1723 at D). After 50 seconds of holding, the slag at stage E was found to be at a uniform temperature with less than 0.1 K deviation, which is considered as “homogeneous”. The slag was quickly cooled in air from stage E to F.

Figure 4(c) shows transient temperatures of the slag at different locations in the crucible. There is no real temperature difference between points O, M, and N (positions shown in Figure 4(a)) during the stages CD and DE because of the slow cooling and holding, respectively. The cooling rate during stage EF resulted from the natural heat transfer coefficients applied as the boundary conditions. The average heat transfer coefficient \( h = 25 \, \text{W/m}^2\text{K} \) (with deviation of \( \pm 5 \, \text{W/m}^2\text{K} \)) was found at the top and bottom wall, whereas \( h = 27 \, \text{W/m}^2\text{K} \) (with deviation of \( \pm 6 \, \text{W/m}^2\text{K} \)) at the side wall (\( h \) is the average value obtained from temperature between 1673 K and 373 K for the outer wall). Temperature at point Q (Figure 4(a)) drops faster during stage EF due to the radiative heat loss at the top interface. Deviations between point Q and points O, M, N at the same time can go up to about 200 K which confirms the finite magnitude of the slag’s thermal conductivity. Non-linear cooling was found for the stage EF. The cooling time was approximately 2 minutes for reduction of temperature from 1723 K (stage C) to about 750 K (stage F).

Note that a curved gas-slag interface formed due to interfacial tension and wetting effects in the 5 mm crucible experiments was not considered in the simulation. This concave interface can lead to greater radiative heat loss due to larger surface area. However, the concave interface also results in reflection of radiative heat back to the slag medium due to the less-than-unity view factor effect which compensated for the heat loss due to larger surface area. The opposing effects were demonstrated in the authors previous work.\[12\]

A simplified version of the above momentum equation can be represented via a characteristic velocity driven by the thermalsolutal convection, which can be written as:
where $L_c$ is the characteristic length. This equation indicates that velocity of the fluid is driven by thermal gradients represented by $\sigma_T$, concentration gradients by $\sigma_C$, and viscous resistance represented by dynamic viscosity $\mu$, which is a function of the liquid fraction $\beta$. For example, for a unit of temperature difference ($\Delta T = 1K$), Eq. [25] gives $v_c \approx 10^{-4}$ m/s at $L_c = 5$ mm, assuming no concentration gradient ($\Delta Y = 0$), and using the above discussed thermophysical properties at 1873 K.

Sequential snapshots of the velocity, liquid fraction, solute, and solvent concentration on the $XY$ plane ($Z = 0$) are shown in Figure 5. Equation [25] demonstrates that there are no flows in the solid region because of the considerable viscous resistance, whereas high velocities can be obtained in the regions of low viscosity and high temperature and concentration gradients. Such regions are likely on the liquid side of the mushy zones shown in Figure 5. Higher velocity magnitudes shown near the bottom and top of the crucible at stage C (at $t = 0.001$ seconds) are due to the difference in the heat transfer boundary conditions at the top and bottom walls ($h = 27$ W/m$^2$K) compared with the side wall ($h = 25$ W/m$^2$K). The highest local velocity was shown to be about $0.13 \times 10^4$ m/s.

Unlike solidification of the pure compounds, the liquid fraction of the binary mixtures is influenced by the convection and diffusion of the two species, as shown between Eqs. [8] and [12]. The mass fraction of the species on the liquidus ($Y_{i,\text{liq}}$), and the solidus side ($Y_{i,\text{sol}}$) was computed by Eqs. [15] and [17], respectively. Mass fraction of species $i$ in the mushy region is bounded between $Y_{i,\text{liq}}$ and $Y_{i,\text{sol}}$. Concentration of each species shown in Figure 5 was obtained in this mushy zone based on the previously obtained liquid fraction.

At the initially homogeneous stage (stage $C$, $t = 0$ seconds), at a temperature of 1873 K, liquid mass fraction was 0.65 comprising Fe-rich phase mass fraction of 0.40 and P-rich phase of 0.60. At stage $D$, liquid mass fraction varied within a range between 0.32 and 0.67 while the mass fraction (concentration) of the Fe-rich and P-rich phase varied between 0.29 and 0.44, and 0.56 and 0.71, respectively. Only slight variations were found during the isothermal stage $DE$ due to thermalsolutal effects and redistribution of the solute. During the fast-cooling stage $EF$, large heat loss at the top interface leads to the first solidified layer, which grows quickly towards the bottom of the crucible at which the heat loss is lowest, because crystals tend to grow in the direction opposite to the heat flow (hotter at the bottom). The P-rich phase, according to the phase diagram, solidifies first so the Fe-rich phase is rejected into the inside area. This diffusion effect quantified by the partition coefficient of solute $K_i$ in Eq. [17] makes the liquid fraction higher in the inside region. The mushy zone with higher liquid content in turn enables the macro-segregation by thermalsolutal convection, which continues until the slag completely solidifies. At the fully solidified state, the liquid fraction or “porosity”

![Figure 6](image-url)

**Table IV. Chemical Compositions of the P-rich and Fe-rich Phase by EDS**

| Composition | P-rich Phase (Wt Pct) | Fe-rich Phase (Wt Pct) |
|-------------|-----------------------|------------------------|
| CaO         | 59                    | 18                     |
| SiO₂        | 21                    | 9.5                    |
| Fe₂O₃       | 0.8                   | 53                     |
| P₂O₅        | 18.4                  | 0.9                    |
| MgO         | 0.3                   | 12                     |
| Al₂O₃       | 0.1                   | 6.5                    |
| Total       | 100                   | 100                    |
becomes zero and therefore velocity becomes zero according to the 'porous media' approach. Segregation occurs most during the stage $EF$ giving the highest concentration of Fe-rich phase of $\sim 0.55$ near the bottom wall, and the highest concentration of P-rich phase of $\sim 0.7$ near the top interface. This increase of $\sim 17$ pct of the P-rich concentration (from 0.6 at stage $C$ to 0.7 at stage $F$) at the top portion is discussed further in the next section.

It is worth noting that the mass fraction snapshot shows a mushy zone 'pocket' at stage $F$ in Figure 5, which is entrapped inside the solid bulk (blue colour). As no diffusion in the solid phase is predicted by the Scheil model, the $Y_{\text{liq}}$ value of the solute (Fe-rich) shown in Eq. [15] is supposed to reach its eutectic stage in this pocket according to the phase diagram in Figure 3. However, this never happens even when the temperature drops below the eutectic temperature. This is because of the high effective viscosity of the suspension, which goes up steeply once solid fraction becomes significant (i.e. from $\sim 25$ pct for the current slag composition). Therefore, there is no real change in the concentration of the P-rich and Fe-rich phases once the system is close to complete solidification (stage $F$), which can be seen in stage $F$ in Figure 5.

Although a lower cooling rate is always considered desirable for segregation, the initiation of the solidification at a desired location during the slow cooling process is necessary. Solidification of the desired species needs to be initiated so that it is not able to be circulated again into the liquid zone by macro-segregation. Therefore, it is essential to commence the solidification at a designed area at which the high concentration of the species is expected (i.e. the P-rich phase in this study). For the purpose of removing phosphorus, it was designed for an open top interface which needs to be cooled down first so that separation of the P-rich phase can be physically performed from the top surface.

2. Experimental results

In the crucible experiments—which was carried out for model validation prior to performing the large-scale simulations—a number of approaches to characterizing the segregation and recovery of the phosphorus have
been evaluated. These are based on scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS), in combination with image analysis and the TESCAN Integrated Mineral Analyser (TIMA-X) techniques. All approaches used to assess the phosphorus segregation showed similar and consistent results.

It can be seen in Figure 6 that coarse dendrites identified as C\textsubscript{2}S–C\textsubscript{3}P (P-rich phase) are present at the top of the crucible while fine grains identified as Fe-rich matrix are present in the bottom portion of the crucible. Chemical compositions of these phases are based on EDS analysis and shown in Table IV. From this analysis.
it can be seen that most P in the slag is in the C2S–C3P, P-rich phase; along with most of the CaO and SiO2. Most Fe2O3, Al2O3 and MgO were found in the Fe-rich matrix phase. Quantitatively, higher concentrations of the P-rich phase was shown in the upper portion and higher concentrations of the Fe-rich phase in the lower portion of the crucible. This is consistent with the model prediction.

Distributions of P2O5 and Fe2O3 matrices along the crucible’s height were quantified and shown in Figure 7. From the area percentage analysis using TIMA-X (Figure 7(b)) the percentage of P-rich phase in the upper half portion is approximately 3 times higher than in the lower half, whereas the Fe content in the lower half portion is approximately 1.5 times the Fe content in the upper half. These partition deviation figures imply the possible segregation of the two main phases. From the mass percentage analysis using EDS (Figure 7(d)), the P2O5 concentration was about 3.8 pct in the slag in the lower portion (approximately 40 wt pct). The slag in the top portion of the crucible (approximately 60 wt pct) has P2O5 concentration of ~ 6.5 pct compared with the initial concentration of 5.5 pct. This means an increase of about 18 pct in the P-rich phase found in the top portion. This agrees reasonably well with the model prediction of ~ 17 pct.

B. Solidification in Industrial Scales

1. 16-Tonne slag pot

Model runs were carried out to simulate solidification and separation of phosphorus in an industrial slag pot. Variations of local temperature at different positions within the slag domain are presented in Figure 8(a), and local wall heat flux are presented in Figure 8(b). Figure 8(a) shows a higher cooling rate at the early stage due to the larger temperature difference between the slag and the surrounding air. Within the slag, temperature difference may be up to 1000 °C due to the finite thermal conductivity of the slag (k = 2 W/mK). No linear cooling rate was found during the 16-hour cooling period. However, an approximate cooling rate ~ 1 K/min obtained from the volume average temperature curve (solid curve in Figure 8(a)) was found in the first 4 hours of cooling, which is frequently quoted as the industrial linear cooling rate in open slag pit or yard (Nguyen et al. 2021). Temperature is lowest at the location adjacent to the wall, and highest at the centre of the pot. Temperature at point M is higher than that at point N because the heat transfer coefficient at top (h = 6 W/m2K) is lower than that at the side wall (h = 7 W/m2K). Temperature at point O is higher than that of point M and N because of the thicker slab placed at the bottom of the slag pot. Figure 8(b) presents the local wall heat flux at different local points M, N, and O. The heat flux, which was computed from the conductive thermal resistance and temperatures at the two sides of the wall, was found to be lower at point O compared with point M and N because of the bottom wall is thicker (higher thermal resistance) than the other sides.

Figure 9(a) shows the temperature distribution after 16 hours of cooling from its initial stage at 1873 K. The black solid line indicates the mass fraction at 0.5. After 16 hours of cooling, a solidified layer (liquid fraction of less than 0.1) was found near the side and the top wall. The thickness was shown to be approximately 18 cm.

Distributions of the P-rich and Fe-rich phases resulted from convection and diffusion using Scheil model, as discussed in the crucible simulations section. For the slag pot, the solidification commenced from the top and side walls which undergo the highest heat loss. Therefore, the earlier solidified layer containing higher phosphorus occurs near the side and top wall. Figure 10 shows the sequential change in velocity, liquid fraction, P-rich, and Fe-rich concentrations at the XY plane (at the centre, Z = 0) during the cooling. Similar to the solidification in the small Pt crucible, higher thermal-solutal convections were found in the liquid region adjacent to the mushy zones where significant gradients of density and concentration exist. After 16 hours of cooling, a thick layer of solid was formed at the wall while a considerable amount of liquid was still found inside the slag pot. The P-rich phase concentration reached its largest value at 0.74 near the walls compared with its initial 0.5. The Fe-rich phase reached 0.69 at the inside region compared with its initial 0.4. This means that the possibility of segregation of the two phases after cooling is significant. Once the slag solidifies, there is no more variation in the species because the Scheil model was used in this study i.e. no back diffusion. Comparable results with the published experimental data are given in the next section.

Figure 11 shows the result reported originally in the work by Pietruck et al (8,23) for the 16-tonne slag pot. After 16 hours of cooling, the solid layer was found at the outside of the slag pot and the thickness was reported to be above 20 cm. The liquid amount was reported at 27 wt pct.

From the present simulation, the ‘solidified layer’ is considered to be the layer with liquid fraction of less than 0.1 (or solid fraction greater than 0.9). The thickness of this layer was found to be approximately 18 cm. The total liquid amount with liquid fraction of greater than 0.5 was found to be approximately 32 wt pct. This liquid quantity was assumed to be similar to

Fig. 11—Solid slag (in the outside) and liquid slag (in the inside) obtained from the 16-tonne slag pot after 16 h of cooling. This figure was reprinted from Ref. 23 with permission, under the terms of the Creative Commons CC BY license.
the liquid that was poured out onto the ground in the work by Pietruck et al.\textsuperscript{[8,23]} i.e. as noted, 27 wt pct. Both the experimental and simulation results found higher P-rich phase near the top lid and side wall. Liquid with higher Fe-rich phase was found in the centre of the slag pot. For the experiment results, the $P_2O_5$ content at the bottom region of the slag pot was reported lower than other regions which may be due to the thick skull amount that decreased heat loss in that region. As summarised in Table V, a comparison between simulations and experimental data show reasonable agreement.

It can be seen that the model prediction of the P-rich phase amount at the top interface is lower compared with the experiments, which can be due to the following facts. It was found that change in the liquidus slope (which is the slope of the line between point (1) and (4) shown in Figure 3) due to either the melting temperature of the P-rich phase or the eutectic temperature, or both, leads to significant change in the liquid mass fraction of the mixture. Attempts were made to evaluate the simulations with an increase in 4 pct in the liquidus slope which results in 5.6 pct (from ~ 0.65 to 0.7) increase in the liquid mass fraction at the initial stage. This leads to an increase in the P-rich mass fraction from 0.74 to 0.78. Therefore, as noted in Section 2.4.3, the phase diagram developed in this study may be an over simplification and not properly represent the slag composition used in the experiments.\textsuperscript{[8,23]} This may be an explanation for the model predicting a lower P-rich phase amount at the top interface, compared with the experiments. Alternatively, it may be due to the kinetics of nucleation and growth.

It is noted that industrial slag pots do not have any lid. The lid used in the above slag pot case was aimed to match the slag pot used in the experiments.\textsuperscript{[8,23]} However, for a slag pot without a lid, the top solidified layer acts as insulation for the inner slag similar to a physical lid. Simulations performed for this slag pot system (i.e. without a lid) showed similar heat transfer, solidification, and segregation behaviours to those with a lid. Figure 12 shows the local temperature at the centre point of the top layer, the volume average temperature, and the volume average liquid fraction during 10 hours of cooling for the slag pot with and without a lid. Although temperature at the top point is about 100 K lower (at the same time) for the pot without a lid due to direct radiation to air, there is no real difference in volume average temperature between the two cases. The difference in the predicted liquid fraction is therefore negligible.

2. 30-Tonne slag pit

Positive segregation between the P- and Fe-rich phases was shown achievable in a slag pot by controlled solidification. However, the practicality for separating each phase is difficult for this geometry, and the number of slag pots required for continuous operation would be prohibitive. Simulation was therefore carried out in a 30-tonne slag pit (~ 10 m$^3$) as shown in Figure 1(c) to investigate the potential phase segregation and separation performance. The slag pit was assumed to be in-ground to utilise insulation of the crust ‘walls’. The
top is open so that the solidified layer from the top enables the separation of this P-rich solids using a slag skimmer or similar system.

Local temperatures at different points during this 30-hour cooling are shown in Figure 13. At the last stage temperature of the slag adjacent to top walls reaches 500 K whilst it is still greater than 1800 K in the inside due to great insulation of the crust walls and the top solidified layer. Cooling rate obtained from the volume average temperature curve was found to be approximately 1 K/min in the first four hours of cooling which was comparable with the 16-tonne slag pot case.

Figure 14 shows sequential changes in (i) velocity, (ii) liquid mass fraction, (iii) concentration of Fe-rich phase, and (iv) concentration of P-rich phase at different solidification stages during cooling at the $XY$ plane (at $Z = 0$) at different stages during cooling. Similar to the above discussed solidification and segregation behaviour, stronger convective flows were present in the regions with low viscosity, and high density or high concentration gradients. A top solid layer was formed due to significant radiative heat loss over the top surface this location. This solidified layer reached a thickness of ~12 cm within the first 10 hours of cooling. However, the layer thickness increased slowly from ~12 to ~23 cm in the next 20 hours of cooling (i.e. thickness ~23 mm at time $t = 30$ hours). This indicates a slower cooling stage once the first solidified layer is formed, which contributed to insulating the slag underneath. In this top solid layer, concentration of the Fe-rich phase reduced from 0.4 (Figure 14(a), iii) to 0.25 (Figure 14(b) and (c) iii) whilst concentration of the P-rich phase increased from 0.6 (Figure 14(a) a, iv) to 0.75 (Figures 14(b) and (c), iv), which indicate a 25 pct positive segregation for the P-rich phase.

For the purpose of separating the P-rich phase from the Fe-rich phase (which is not the main scope of this study), and if a slag skimmer or similar is to be used, then this has to be carried out while the lower portion of the slag (containing Fe-rich phase) is still in its liquid state. Therefore, it is important to link the solidification stage with an appropriate separation practice to ensure separation of the two phases. For the above slag pit, at $t = 30$ hours, the volume of the P-rich phase with concentration of 0.75 was found at ~23 cm$^3$ (equivalent to the above 23 cm solidified layer). Modelling suggested that ~23 wt pct of the P-rich phase can be separated with 25 pct increase in its concentration.

V. CONCLUSION

This study presented a CFD model based on the enthalpy-porosity approach to model the solidification and segregation characteristics of BOF slag. This was based on a simplified binary phase diagram using information from the FeO–CaO–SiO$_2$ slag ternary diagram. The simulations were carried out to investigate the cooling, solidification, and segregation behaviour of the two main phases present in BOF slag: a P-rich, C$_2$S–C$_3$P phase and a Fe-rich phase.

The model was first applied to simulate a laboratory experiment conducted in a 5 mm diameter Pt crucible. Both simulations and experiments showed phase segregation involving a P-rich phase in the top region of the crucible and a Fe-rich phase in the bottom region. The increase in concentration of the P-rich phase predicted by the model was found to be comparable with the experimental result i.e. 17 vs. ~18 pct, respectively.

The same synthetic slag and similar approach for the crucible were applied to simulate the solidification in a typical industrial slag pot of 16 tonne capacity. Both simulations and experiments showed phase segregation involving a P-rich phase in the top region of the crucible and a Fe-rich phase in the bottom region. The increase in concentration of the P-rich phase predicted by the model was found to be comparable with the experimental result i.e. 17 vs. ~18 pct, respectively.

The same synthetic slag and similar approach for the crucible were applied to simulate the solidification in a typical industrial slag pot of 16 tonne capacity. A volume average linear cooling rate of about 1 K/min was found for the first four hours, which reduced significantly afterwards because of the finite heat conduction of the solidified slag and the reducing slag-air temperature difference. Segregation between the P and Fe-rich phases was shown to be significant in the slag.
Fig. 14—Sequential snapshots of (i) velocity, (ii) liquid mass fraction, (iii) concentration of Fe-rich phase, and (iv) concentration of P-rich phase at different solidification stages during cooling. (a) at 100 s; (b) at 10 h; (c) at 30 h.
solidified layer at top reached a thickness. The results showed that after 30 hours of cooling, the heat loss at the top interface due to the strong radiation. An in-ground rectangular slag pit benefiting from large scale slag pots, the practicality of accomplishing such separation is challenging in such equipment. Therefore, this phase separation was proposed to be carried out in an in-ground rectangular slag pit benefitting from large heat loss at the top interface due to the strong radiation. The results showed that after 30 hours of cooling, the solidified layer at top reached a thickness ~23 cm occupying a volume ~2.3 m³, and an increase of the P-rich phase concentration of ~25 pct.

Further in-depth simulations are necessary to confirm the separation performance, and these should include investigation of the primary precipitation and other phase transformation as a function of slag composition and cooling rate. The validated results can be used to improve the separation efficiency in slag pits. The validated model can also be applied in continuous operation such as a slag cleaning furnace involving a gas sparging facility.

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CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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