Variability in ferroalloy furnace tapping – insights from modelling

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Abstract – During tapping of pyrometallurgical smelters, molten products from the furnace operation are periodically removed from the vessel. Variations in the quantities of alloy and slag obtained from each tap are undesirable and can cause disruption to upstream and downstream operations, resulting in economic losses and safety risks to plant personnel. In the present work an integrated reduced-order model of a ferroalloy furnace tapping system was used to assess the sensitivity of the process to various operating parameters, and describe the statistical impact of random changes in the system over a large number of tapping cycles. The effect of implementing simple control measures to determine the best point to stop a tap is also presented.

INTRODUCTION

The production of ferroalloys such as high-carbon ferromanganese (HCFeMn) in submerged-arc electric furnaces (SAF) is a complex process, and requires a number of interconnected operations to function together correctly. A critical component in the operation chain is tapping, the process of removing molten alloy product and waste slag from the furnace at regular intervals. This is usually accomplished by opening a channel in a specialized section of the furnace lining (the tap-hole) and allowing the contents to drain out of the vessel under the action of gravity and internal furnace pressure, and resealing the channel when drainage is complete (Nelson and Hundermark, 2016). In HCFeMn processes a single-level tap-hole is often used, and slag and metal phases are tapped through it simultaneously (Davidsen and Honstad, 2018).

Figure 1: Parts of a real tapping system in operation at a South African producer of manganese ferroalloys (© Joalet Steenkamp)
After exiting the furnace via the tap-hole channel, the stream of molten material is directed along launderers into storage vessels. These range from simple sand pits to dedicated tapping ladles, and are generally arranged in sequence so that the overflow from one vessel fills the next. The combination of the furnace tap-hole and tapblock, launderers, and storage vessels is referred to as a tapping system, and is serviced by ancillary equipment which facilitates opening and closing the tap-hole, removing the tapped product, and so forth. Photographs of a typical operation are shown in Figure 1, and Figure 2 gives a schematic of the furnace tapping system showing the separate components.

A number of factors can influence the tapping system behaviour during any given tap including conditions inside the furnace prior to and during the tap (especially the disposition of the porous burden layer in the vicinity of the tap-hole), the condition of the tap-hole channel, and the geometry and arrangement of the ladle strand. Some variation in these parameters is unavoidable even during periods of optimal furnace operation, and can result in significant differences in the masses of product and waste materials obtained from each tap. Such variation can negatively affect direct product losses (for example metal carried over from the first ladle into the “discard” or “slag” ladles later in the strand) as well as downstream operations (slag-metal separation, secondary ladle treatments, and transportation logistics). Inconsistencies in tapping also elevate the risk of extreme events such as equipment failures, spillages, and runaway taps, all of which are potentially hazardous to personnel working near to the furnace.

Due to the difficult working environment, control of the tapping system on ferroalloy furnaces is generally performed in a relatively simple fashion by fixing the intervals between taps as well as the tap duration. In addition, certain secondary measures such as the total flowrate in the tapping stream or the level of metal in the first ladle may be used to indicate when early closure of the tap-hole is advisable.

A number of efforts have been made to assess the performance of furnace tapping systems using numerical simulation. Computational modelling, which includes computational fluid dynamics and coupled multiphysics methods, has traditionally focused on the tap-hole channel and surrounding regions (Muller and Steenkamp, 2013), although recent work has begun to examine the behaviour of ladles (Johansen and Ringdalen, 2018). Unfortunately such methods are very computationally expensive, and these studies are by necessity limited to a small number of cases and short time-frames. In contrast a number of reduced-order models of the tapping process have been developed, and use simplified physical descriptions of the fluid flow inside the furnace and tap-hole to permit much faster calculation (Iida et al., 2008) (Muller et al., 2015). The extension of such reduced-order models with similar descriptions of
the flow behaviour in transfer launders and ladles was deemed to be of value for building further intuition on the behaviour of furnace tapping systems.

**MODEL DESCRIPTION**

In order to construct a reduced-order model of the HCFeMn tapping system as shown in Figure 2, it is convenient to split the system into four components: The furnace interior, the tap-hole channel, the transfer launder or runner, and the ladle strand.

A detailed pressure balance calculation for multiphase flow of material through the porous burden and into the tap-hole has been developed by the authors in previous work (Olsen and Reynolds, 2020). This model is able to account for the effect of converging flow through a porous burden layer, cavities in the burden around the tap-hole entrance, pressure losses due to entrance effects and channel flow, and multiphase entrainment and interface deformation during simultaneous tapping of both phases. This model was combined with a simple dynamic mass balance over the furnace interior; over a given time step the generation of slag and metal is calculated as a function of the applied power and specific energy requirement of the raw materials. This is shown in equation (1), with $\dot{m}_{m, in}$ and $\dot{m}_{s, in}$ the rate of metal and slag generation, $P$ the furnace power input, $\cos \theta$ the AC power factor, $SER_m$ the specific energy requirement of the process, and $MSR$ the ratio of slag to metal mass produced during reductive smelting. The outlet mass flowrates are determined from the pressure balance flow model (if the tap-hole is open). Positive or negative accumulation in the furnace then determines any changes in the slag and metal levels in the vessel.

$$\dot{m}_{m, in} = \frac{P \cos \theta}{SER_m}$$

$$\dot{m}_{s, in} = MSR \cdot \dot{m}_{m, in}$$

(1)

The transfer launder is a multiphase open channel flow problem, and for the purposes of the present work was treated as a simple instantaneous single-input, single-output mass balance with no accumulation or loss of material.

Each of the tapping ladles is treated as a multiphase dynamic mass balance, with inlet of slag and metal defined by the outlet of the previous ladle in sequence (or the furnace tap-hole in the case of the first ladle), and outlet defined by any overflow of the two phases once the ladle is filled to its maximum depth. A degree of mixing of metal droplets into the slag layer is frequently observed during ladle tapping (Eidem et al., 2015) and should be accounted for to ensure accuracy of the mass balance. This mixing effect has been confirmed and quantified using computational fluid dynamics models (Johansen and Ringdalen, 2018) (Reynolds and Olsen, 2021), and the data from such studies may be used to generate a simplified empirical expression which describes the entrained metal fraction in the slag layer as a function of the slag layer thickness. This is shown in equation (2) with $\chi_m$ the fraction of metal entrained in the slag, $H_m$ and $H_s$ the height of the slag-metal interface and the top of the slag respectively, and $A$ and $B$ representing empirical fitting constants.

$$\chi_m = A \exp(-B(H_s - H_m))$$

(2)

It should be noted that the entrained metal fraction will in general also depend on the location and strength of the inlet stream, and the positioning of the ladle outlet relative to it – in the interests of simplicity, this dependence has been neglected in the present work.
The governing equations of the tapping system model are integrated in time using an explicit forward-Euler time stepping algorithm, to achieve high temporal resolution while minimising computational expense. Time step sizes were limited to 5 s in order to retain acceptable accuracy and stability.

The model was embodied in a portable Python v3.9 (Python Software Foundation, 2020) package with a hierarchical class structure consisting of various extensible sub-models for the furnace interior, tap-hole, transfer launders, and ladles. After installation of the package on a suitable Python distribution, integrated tapping system models can be easily and quickly constructed either using predefined templates or by direct assembly from the sub-model classes. Parallelisation of large statistical ensembles of tapping system simulations for execution on high performance computing architectures was accomplished with mpi4py v3.0.3 (mpi4py, 2020) compiled against MPICH v3.4.1 (MPICH, 2020).

**RESULTS AND DISCUSSION**

Table 1: Base case model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace power</td>
<td>$P$</td>
<td>48 MVA</td>
</tr>
<tr>
<td>Power factor</td>
<td>$\cos \theta$</td>
<td>0.7</td>
</tr>
<tr>
<td>Process specific energy requirement</td>
<td>SER$_m$</td>
<td>3.5 MWh/t</td>
</tr>
<tr>
<td>Slag:metal production ratio</td>
<td>MSR</td>
<td>0.8</td>
</tr>
<tr>
<td>Furnace internal diameter</td>
<td>$D_F$</td>
<td>12 m</td>
</tr>
<tr>
<td>Furnace active area fraction$^1$</td>
<td>$\alpha_A$</td>
<td>0.75</td>
</tr>
<tr>
<td>Diameter of burden particles</td>
<td>$D_{p,b}$</td>
<td>0.03 m</td>
</tr>
<tr>
<td>Sphericity of burden particles</td>
<td>$\psi_{p,b}$</td>
<td>0.8</td>
</tr>
<tr>
<td>Burden porosity</td>
<td>$\phi_b$</td>
<td>0.4</td>
</tr>
<tr>
<td>Diameter of burden cavity at tap-hole entrance$^2$</td>
<td>$D_{b,min}$</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Tap-hole diameter</td>
<td>$D_t$</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Tap-hole length</td>
<td>$L_t$</td>
<td>1 m</td>
</tr>
<tr>
<td>Tap-hole centrel ine height$^3$</td>
<td>$H_t$</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Tap-hole channel surface roughness</td>
<td>$\epsilon_t$</td>
<td>0.001 m</td>
</tr>
<tr>
<td>Tap-hole entry pressure loss coefficient</td>
<td>$K_t$</td>
<td>0.25</td>
</tr>
<tr>
<td>Ladle internal depth</td>
<td>$H_L$</td>
<td>2.2 m</td>
</tr>
<tr>
<td>Ladle internal diameter</td>
<td>$D_L$</td>
<td>2 m</td>
</tr>
<tr>
<td>First entrainment constant</td>
<td>$A$</td>
<td>0.576</td>
</tr>
<tr>
<td>Second entrainment constant</td>
<td>$B$</td>
<td>30.1/m</td>
</tr>
<tr>
<td>Metal density</td>
<td>$\rho_m$</td>
<td>5600 kg/m$^3$</td>
</tr>
<tr>
<td>Metal viscosity</td>
<td>$\mu_m$</td>
<td>0.005 Pa.s</td>
</tr>
<tr>
<td>Slag density</td>
<td>$\rho_s$</td>
<td>2800 kg/m$^3$</td>
</tr>
<tr>
<td>Slag viscosity</td>
<td>$\mu_s$</td>
<td>1 Pa.s</td>
</tr>
<tr>
<td>Tap-to-tap interval</td>
<td>$\tau_{t-t}$</td>
<td>4 h</td>
</tr>
<tr>
<td>Tap duration</td>
<td>$\tau_{tap}$</td>
<td>0.5 h</td>
</tr>
</tbody>
</table>

$^1$Defined as the portion of the total furnace cross-sectional area occupied by the molten bath  
$^2$The size of the hemispherical region in front of the tap-hole which is clear of burden particles  
$^3$Relative to hearth level  
$^4$Active depth between ladle hearth and overflow
In order to provide a reference point for all calculations using the tapping system model, a base case set of parameters was defined using information collated for a number of different furnace studies related to HCFeMn production (Olsen et al., 2007) (Tangstad, 2013) (Steenkamp and Basson, 2013) (Steenkamp et al., 2014) (Muller et al., 2015) (Steenkamp et al., 2017) (Steenkamp et al., 2018a) (Steenkamp et al., 2018b) (Steenkamp et al., 2019). The full base case parameter set is shown in Table 1, and represents a choke-fed circular submerged-arc furnace operated with a deep burden layer and a single tap-hole, and a single strand of three identical tapping ladles.

Results from the base case simulation for the first few taps starting from an empty furnace are shown in Figure 3. It can be seen that the levels in both the furnace and the tapping ladles converge to a unique steady state defined by the parameters of the furnace process and the operation of the tapping system, with the first ladle filling nearly completely with metal and the subsequent ladles containing mostly slag during each tap.

Figure 3: Evolution of slag and metal levels in furnace tapping system over time (tap-hole centreline is shown by dashed line on top graph)
Per-tap information can also be generated by appropriate analysis of the time series data. The tap masses obtained in this fashion are shown in Figure 4. Here, metal product is assumed to be the mass of metal in the first ladle, and metal lost is assumed to be all remaining metal which is carried over to the other ladles in the strand. In this case it appears that the system converges to a repeatable cycle after ten taps, or approximately 40 hours of operation; any changes made to the furnace or tapping operation may therefore be expected to show a similar lag before their effects become fully developed.

**Sensitivity analysis**

Although it is highly simplified, it is instructive to study how the tapping system model reacts to changes in the various parameters that define its behaviour. In order to do this multiple simulations were executed, varying each of the parameters independently while holding the others constant at the values given in Table 1. Each simulation was run for 60 taps, and the result of the final tap was taken as the converged result. Several output variables for the furnace tapping operation were defined and calculated for the final tap:

- Average metal level in the furnace, $H_{m,avg}$
- Average slag level in the furnace, $H_{s,avg}$
- Peak metal tapping flowrate, $\dot{m}_{m,max}$
- Peak slag tapping flowrate, $\dot{m}_{s,max}$
- Total metal mass obtained per tap, $M_{m,tap}$
- Total slag mass obtained per tap, $M_{s,tap}$
- Metal losses per tap, $M_{m,lost}$

A normalised dimensionless sensitivity was then defined as shown in equation (3), where $x_i$ is any one of the independent model parameters and $y_j$ is any one of the dependent output variables defined above. The exception to this is the sensitivity of $M_{m,lost}$ which is normalised relative to $M_{m,tap}$ instead of itself. The derivative in equation (3) was approximated numerically by making small changes in each independent parameter and calculating the resulting change in the dependent variables obtained from the tapping system simulation.

$$
\sigma_{ij} = \frac{x_{i,base}}{y_{j,base}} \frac{dy_j}{dx_i}
$$

(3)

The results of the sensitivity analysis for selected parameters are given in Figure 5, where the sign of $\sigma_{ij}$ is represented by colour (red for positive, blue for negative) and the area of the circle is proportional to its magnitude.
Only the furnace power, SER, MSR, and tap timings affect the total amount of metal and slag produced in each tap. This is as expected, since none of the other parameters affect the overall mass balance of the operation. In the material properties the largest sensitivity is to the slag density, followed by the slag viscosity and metal density. Metal viscosities are generally very low and therefore have negligible impact on the behaviour of the tapping system unless they change dramatically. Of the tap-hole parameters, only the diameter is seen to have an appreciable effect, with the length and entrance loss sensitivities small in comparison to other parameters. Although they do not affect the external operation (tapped masses) significantly, the parameters describing the particles and geometry of the burden in the vicinity of the tap-hole entrance have a very large influence on the interior conditions of the furnace and the tapping rates. In particular the burden porosity and tap-hole entrance cavity size have strong effects, and these may easily change from tap to tap due to the invasive processes involved in opening, operating, and closing the tap-hole. On the majority of ferroalloy furnaces this includes a combination of rapid drilling and thermal lancing to open the channel, both of which can damage the tap-hole and tapblock if performed incorrectly. Drilling or lancing into the furnace interior, which is generally unavoidable to some degree, also changes the burden structure by disrupting the loose bed of material in the critical area around the tap-hole entrance. Improvement in the robotic automation of opening methods is ongoing, but obtaining a repeatable tap-hole and furnace configuration after opening remains a significant engineering challenge.

It is important to recall that these are only first-order sensitivity calculations and while useful to indicate the general shape of the system’s response space, caution should be taken in applying them directly to operating plants as-is. In reality many ongoing adjustments to operational variables (power input, tap timings) will be made by experienced operators taking into account any equipment repairs or alterations (tap-hole dimensions, ladle sizes) in order to maximise the process’s efficiency while minimising product losses.

**Variability analysis**

As seen in the sensitivity analysis, variation in any of the parameters of the furnace tapping system may cause a variety of changes in the results obtained during any given tap. In order to assess the overall effect of multiple sources of variability acting together, a series of simulations was performed in which several of the model parameters were randomly altered once during each tapping interval.
Of the full tapping system parameter set only the furnace power $P$, area fraction $\alpha_A$, slag viscosity $\mu_s$, tap-hole diameter $D_t$, burden fraction $\phi_b$, and burden cavity diameter $D_{b,\text{min}}$ were thought likely to exhibit random fluctuations between successive taps – the other parameters either do not change at all or do so in slower, more predictable ways. This subset was therefore used in all the following simulations. The parameters were sampled from a uniform distribution between 97.5% and 102.5% of the base case values given in Table 1, i.e. a 5% variation centred on the mean value. Large ensembles of simulations were then run in parallel to simulate tapping system behaviour over long periods of time (the equivalent of 600 years of furnace operation, representing 1 – 1.5 million taps) in order to generate data sets suitable for statistical analysis.

As a reference case, simulations were performed with no secondary control actions in place to change the tapping time. This therefore remained fixed at 30 minutes for every tap as per the base case specification. Selected results from the tap sequence are shown in Figure 6. Variability in the tap masses is quite high, as is the variability of the slag level inside the furnace. A statistical analysis of the full data set is presented in Figure 7, with comparisons to the standard gamma probability density function for positive-only values. It can be seen that even with relatively small deviations in the input parameters, a moderate to large spread of results is possible in any given tap. The data also distribute very close to statistically-normal in this case.

Note that in Figure 7 and all following figures, the y-axis scales are adjusted to the maximum value of the gamma distribution to permit easier qualitative comparison between variables – the total area under the probability density distribution curves sums to unity in each case.

![Figure 6: Tapping system variability with no secondary control](image-url)
Secondary control measures for the tapping system were then introduced. In the next set of variability simulations, each tap was stopped early if the level of slag in the final ladle exceeded 1.2 m. This has the effect of putting an upper limit on the total volume of material tapped. Comparing Figure 8 with Figure 6, it can be seen that this control measure offers a significant reduction in variability of the total tapped mass. This comes at the expense of a slight increase in the slag inventory in the furnace, with slower low-frequency fluctuations lasting many taps. Comparing Figure 9 with Figure 7 shows that the spread of values for slag mass is decreased substantially, and the metal losses are also slightly reduced. Tap durations distribute around approximately 0.45 h, close to the limit of 0.5 h. The data again distribute statistically-normal for the most part.

Figure 8: Tapping system variability with tap volume control (left: average slag and metal levels inside furnace, right: tapped masses)
In the next set of simulations, each tap was stopped early if the thickness of the slag layer in the first ladle dropped below 0.1 m. This is generally implemented in an attempt to limit any significant metal losses into the discard slag ladles. Comparing Figure 10 with Figure 6, this control action has a major effect on the behaviour of the entire furnace tapping system. Tapped metal masses are very consistent, but much larger fluctuations in both the slag mass and the furnace slag inventory are observed. Comparing Figure 11 with Figure 7 shows that the spread of values for almost all variables is increased with the exception of tapped metal masses and metal losses, both of which show much less variation. Average metal losses are also greatly reduced. In this case the data show some appreciable deviations from statistically-normal distributions, particularly for furnace metal levels and tapped slag masses.
Figure 11: Tapping system variability with slag thickness control showing probability density distributions of dependent variables (grey bars: simulation data, black lines: gamma distribution best fit, dashed line: mean value)

In the next simulation set, each tap was stopped early if the total flowrate of material out of the furnace tap-hole dropped below 1.3 t/min. This type of control measure is typically implemented to avoid material freezing and causing tap-hole opening difficulties during the subsequent tap. Comparing Figure 12 with Figure 6, this control action has the most significant impact on the variability of slag and metal tapped masses, increasing both significantly, while also slightly increasing the slag inventory in the furnace. Comparing Figure 13 with Figure 7 shows this effect clearly with the spread of values on slag and metal tapped masses increasing substantially. Average metal losses are slightly reduced although there remains considerable deviation from tap to tap. The results distribute statistically-normal for the most part with the exception of the slag tap mass, which shows some truncation effects similar to those observed in the slag thickness control case.

Figure 12: Tapping system variability with tap flowrate control (left: average slag and metal levels inside furnace, right: tapped masses)
In the final simulation set all three of the limit measures described above (tap volume control, slag thickness control, and tap flowrate control) were implemented simultaneously.

Comparing Figure 14 with the earlier results, it can be seen that although imposing a lot of control on the tapping process results in relatively smooth operation in terms of the tap masses, it also causes large fluctuations in the furnace inventory – this can be expected to negatively impact the stability of the furnace chemistry and heat transfer, potentially resulting in process control difficulties elsewhere. Figure 15 supports this, with variability in the “observable” parts of the tapping system (tap masses and metal losses) being reduced while the “hidden” parts of the system (furnace interior) are much more noisy. The average tapping duration also drops to approximately 0.3 h in this case, and the practicalities of getting tap-holes opened and closed in such short time-frames are likely to become limiting. Interestingly the statistics of the slag level as well as the tapping flowrates distribute statistically-normal, while other variables such as the metal level and tap masses show extreme deviations as a result of the control actions skewing the data.
Figure 15: Tapping system variability with all control measures showing probability density distributions of dependent variables (grey bars: simulation data, black lines: gamma distribution best fit, dashed line: mean value).

Table 2: Mean and standard deviation of output variables in tapping variability simulations

<table>
<thead>
<tr>
<th></th>
<th>No control measures</th>
<th>Tap volume control</th>
<th>Slag thickness control</th>
<th>Tap flowrate control</th>
<th>All control measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std</td>
<td>Mean</td>
<td>Std</td>
<td>Mean</td>
</tr>
<tr>
<td>$H_{m, \text{avg}}$</td>
<td>0.141</td>
<td>0.00132</td>
<td>0.143</td>
<td>0.00204</td>
<td>0.148</td>
</tr>
<tr>
<td>$H_{s, \text{avg}}$</td>
<td>0.873</td>
<td>0.0220</td>
<td>0.959</td>
<td>0.0220</td>
<td>1.14</td>
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<td>$m_{n, \text{max}}$</td>
<td>143</td>
<td>7.01</td>
<td>147</td>
<td>6.76</td>
<td>157</td>
</tr>
<tr>
<td>$m_{s, \text{max}}$</td>
<td>19.8</td>
<td>1.36</td>
<td>21.7</td>
<td>1.43</td>
<td>25.8</td>
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<tr>
<td>$M_{m, \text{tap}}$</td>
<td>38.4</td>
<td>1.16</td>
<td>37.9</td>
<td>0.930</td>
<td>37.2</td>
</tr>
<tr>
<td>$M_{s, \text{tap}}$</td>
<td>30.8</td>
<td>1.96</td>
<td>30.3</td>
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<td>29.6</td>
</tr>
<tr>
<td>$M_{m, \text{lost}}$</td>
<td>1.09</td>
<td>0.963</td>
<td>0.699</td>
<td>0.601</td>
<td>0.215</td>
</tr>
<tr>
<td>$\tau_{\text{tap}}$</td>
<td>0.500</td>
<td>-</td>
<td>0.447</td>
<td>0.0304</td>
<td>0.368</td>
</tr>
</tbody>
</table>

Quantitative results from all the tapping system variability simulations are summarised in Table 2. The mean and standard deviation were calculated from the fitted gamma distributions, and while useful as an indicator of general trends should be used with caution in cases where the data is not normally distributed.

CONCLUSIONS

The development of a reduced-order model for integrated furnace tapping systems was successfully completed, and demonstrated by being applied to a generic HCFeMn process. Baseline simulations using this model showed that the tapping system responded slowly to start-up and change conditions, with relaxation times of the order of 10 taps.

The model’s response to process changes was explored using a first-order sensitivity analysis. This showed that changes to power input, process chemistry parameters, and tap timings were the most generally disruptive, while other parameters such as metal density, tap-hole
diameter, and burden properties had a very large but more selective impact on only certain parts of the process.

The nature of variability in furnace tapping was studied using the model, by employing large-scale simulation ensembles with randomly-changing parameters. This showed that a small degree of randomness in multiple parameters was able to produce significant variability in the results obtained from any given tap. Applying various secondary control measures to the tapping process was generally able to reduce the overall metal losses, but often at the expense of increasing variability in other parts of the process – especially the conditions in the furnace interior.

Future work will initially focus on completing validation of the tapping system model against industrial data from operating furnaces. Extension of the model to include different furnace, launder, and ladle designs will also be of value in simulating a wider variety of furnace tapping systems. It is also anticipated that such models may find some industrial application as virtual prototyping and digital twinning tools; for this purpose the ability to design and then optimise a given model to match the operation of a particular plant will be desirable. Platforms combining “top down” data-driven machine learning and artificial intelligence techniques with simplified “bottom up” reduced-order models such as this are therefore likely to be an promising area of future research and development on integrated furnace tapping systems.

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