Integrated Process Modelling for the Kalgoorlie Nickel Smelter

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ABSTRACT

An in-depth process model was developed for the pyrometallurgical, off-gas systems, and water balance of the Kalgoorlie Nickel Smelter. This model was used to assess plant capacity with changing concentrate grades, increased throughput, and tighter environmental emissions under a range of potential future operating conditions. Comparison of modelled results allowed for flowsheet optimisation across a range of metrics including sustainability, processing capacity and costs.

Process modelling software, METSIM®, was used to simulate the flash furnace, integrated electric slag cleaning furnace, Pierce-Smith converters, matte granulation, waste heat boiler, hot gas handling equipment, wet gas cleaning plant, and acid plant. The METSIM® model was divided into three separate, yet interconnected models: metals, off-gas, and water balancing. This allowed for improved modelling efficiency and traceability while minimising manual error.

The METSIM® model was supported by inputs from other specialised software. Chemical thermodynamics software, FactSage™, was used to establish relationships for the flash furnace fluxing strategy and determine the operating temperature. Arena®, a discrete event modelling software, was used to simulate material movements within the aisle as well as Pierce-Smith converter operation, allowing for integration with upstream and downstream systems. A dynamic data exchange (DDE) was used to connect the results of each software package, interfacing through Excel. The integration between models provided a streamlined approach to test capacity, bottlenecks, water consumption and emissions under a range of operating conditions, enabling a more robust process.

Further downstream modelling techniques were used to assess mechanical equipment. METSIM outputs provided key parameters for combustion assessments using computational fluid dynamics, and finite element analysis for the furnace mechanical design.

INTRODUCTION

The Kalgoorlie Nickel Smelter (NKS) was commissioned in December 1972 and has increased from a nameplate capacity of 30 to 100 ktpa Ni-in-matte. The final matte grade is approximately 68% Ni, 2-3% Cu and 1% Co produced from a concentrate feed grade of 12 to 15% Ni. Approximately 500 ktpa of concentrated sulphuric acid is also produced.

The original 1972 flowsheet included a flash furnace, separate electric slag cleaning furnaces, Peirce-Smith converters, and off-gas heat recovery system to generate power. In December 1978 the smelter was upgraded to a unique, larger furnace incorporating flash smelting and slag cleaning within a single furnace, known as an integrated flash furnace (IFF), as described by Hastie et al (1984). Palmer, Malone, and Loth (2005) summarise how NKS was progressively upgraded across several campaigns to increase capacity, align with technological developments, lengthen furnace campaign, and meet environmental standards. The current flowsheet has been optimised around the 1978 IFF flowsheet, with the inclusion of a 525 t/day oxygen plant in 1993, an acid plant for SO_2 capture commissioned in 1996, and an upgraded furnace in 2008.

The current flowsheet is provided in Figure 1. The key areas include:

- Concentrate receival (by rail)
- Flux and revert preparation plant
- Oxygen production plant
- Air preheater
- Integrated flash furnace
- Peirce-Smith converters
- Matte granulation
- Power generation
- Off-gas cleaning including acid plant
- Effluent treatment

The smelter receives nickel concentrate from Leinster, Mount Keith and the Kambalda concentrators. The flash furnace operates with a slag temperature of 1330°C, with the final slag heated to 1350°C as it passes two electrodes sets located in the slag cleaning end of the integrated furnace, known as the appendage. Low-grade matte containing 48% Ni is produced along with discard final slag skimmed from the appendage. The matte is tapped from the furnace and blown through to final matte in three Peirce-Smith converters (PSCs) at 1250°C. The high-grade matte produced is granulated for further processing at the Kwinana nickel refinery or dried and packaged for export.

The smelting process produces SO_2-rich off-gas, the treatment of which includes heat and dust recovery, a wet gas cleaning plant (WGCP), and acid plant. A waste heat boiler (WHB) cools the furnace off-gas to approximately 350°C with superheated steam used to generate electricity for site use and sale to the grid. Electrostatic precipitators (ESPs) further remove dust before a series of scrubbers and wet ESPs remove halides and minor elements including arsenic and selenium. A double-contact double-absorption metallurgical acid plant produces 98.5% sulphuric acid. Converter off-gas is treated with spray coolers and dust collection cyclones, then either discharged to the atmosphere via a stack when wind conditions are suitable to ensure populated areas are not impacted, or further treated in the acid plant. Weak acid effluent from off-gas cleaning is treated for neutralisation and arsenic fixation before disposal to storage. The major sources of water loss from the process are from evaporative cooling water systems for the acid plant and furnace.

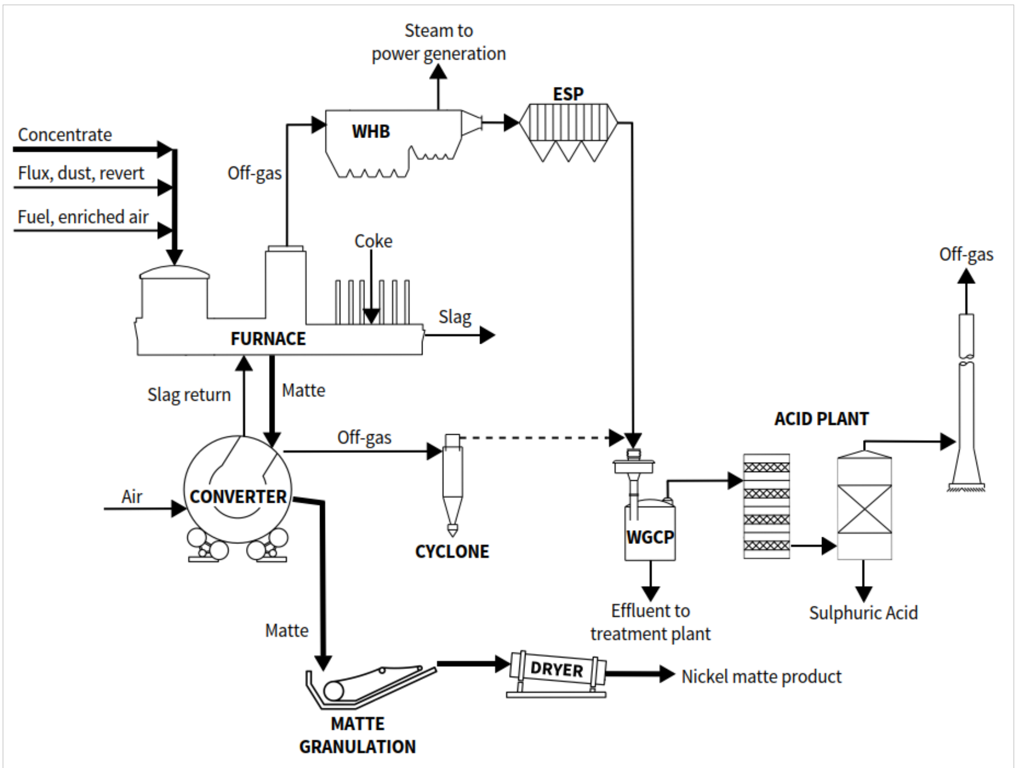

FIG 1 – Process Flow Diagram of Kalgoorlie Nickel Smelter

The last major furnace rebuild at the Kalgoorlie nickel smelter occurred in 2008, with the current campaign being the longest in the sites' history. The business is now in the planning stages for a rebuild, presenting the opportunity to make strategic investments aligned with future business objectives, such as increased operating range, OPEX reduction, and improved health, safety, environmental and community outcomes. A key process consideration was to evaluate the treatment of higher levels of magnesia in the feed, which typically requires higher furnace operating temperatures for processing.

Flowsheet optimisation generally requires an understanding of the interactions between metallurgical (concentrate, flux and molten metals), off-gas, and water systems. For this purpose, a site-wide integrated model with equipment-level definition has been developed using multiple software packages. This paper outlines the development and applications of this model.

MODEL DEVELOPMENT

Process modelling of the smelter was developed primarily in METSIM. Due to the complexity of the plant and software limitations, other software packages were used to supplement the modelling and provide metallurgical and scheduling based inputs. FactSage was used to establish relationships for the flash furnace fluxing strategy and determination of operating temperature. Arena was used to simulate material movements within the converter aisle and the batch operation of the Pierce-Smith converters.

FactSage

FactSage thermodynamic modelling software was used to determine the desired slag composition over a range of potential future operating temperatures and feed compositions. For a given operating slag temperature and superheat, the silica flux addition was varied with Fe/MgO in the concentrate blend supplied to the furnace. The concentrate Fe/MgO was then related to a target slag SiO_2/MgO, and this relationship was used within METSIM to set the flash furnace fluxing requirements for all cases. This FactSage approach is similar to the methodology used to determine fluxing requirements for the current operation (Grimsey, Grimsey and Björklund, 2021). As shown in Figure 2, processing of higher MgO (low Fe/MgO) concentrates requires increased silica fluxing for a given slag temperature and superheat. Details of how this relationship is obtained can be found in Grimsey, Grimsey and Björklund (2021).

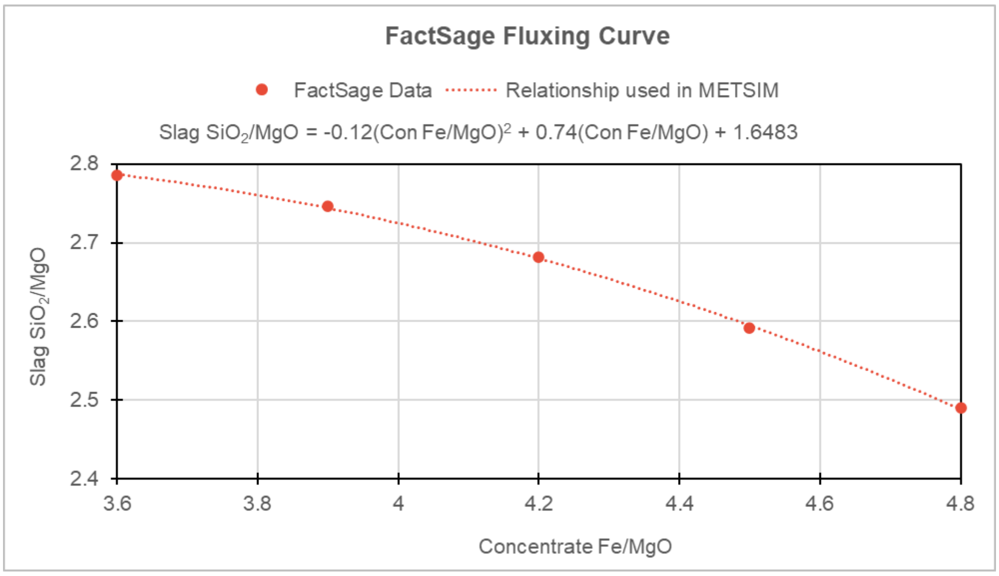

FIG 2 – Example fluxing curve generated using FactSage

Arena

The PSCs operate batch processes and their production rate can be constrained by ladle movements within the crane aisle. To aid in debottlenecking and capacity analysis, Arena, a discrete event modelling (DEM) software was used to model the system operations. An existing Arena model was used, which had been developed and updated by OPTSIM®.

Key inputs to the Arena model include furnace feed, maintenance schedules and personnel availability, physical constraints such as size and number of converters and ladles, metallurgical targets, number and speed of cranes, tuyere-line blast air rates, tapping times, and the number of converters blowing at once due to limitations of the acid plant.

The model was used to ensure production targets can be met and for evaluating aisle productivity and bottlenecks. Sensitivity testing was completed to determine the optimal charge pattern, effect of number of converters, metallurgy, and ladle sizes on aisle productivity. It was found that the converters were generally limited by the furnace matte production rate. Arena outputs were fed into the METSIM model; this included the converter charge pattern and ladle sizes in the pyrometallurgy model and blowing frequency in the off-gas model.

METSIM

METSIM is a process simulation software package used to facilitate modelling of complex processes for the metallurgical, chemical, and minerals processing industries.

There are many pre-programmed blocks for specific unit operations available in METSIM, with generic mixer and splitter blocks primarily used for this application. Chemical reactions and their extents, heat transfer, pressure changes, and phase separation are all manually inputted, allowing for complete visibility of the unit functionality. Reaction extents included partition coefficients of Ni, Cu and Co, metallurgical targets such as matte grades, and vapour pressure correlations for off-gas systems. Setpoints and correlations were derived from plant operating data where possible, or from literature and in-house knowledge.

METSIM uses a built-in thermodynamic database for a range of solids, liquid, molten, and gas phase components from various references. Several additional components were added to the model database, for example, pentlandite from a FactSage database. The concentrate feed mineralogy was reproduced (including pentlandite, talc, serpentine, and chlorite) instead of using simplified components, to account for the enthalpy of decomposition.

The smelter model was divided into three separate METSIM models: pyrometallurgy, off-gas and water balance as depicted in Figure 3. This enabled the models to be built, calibrated, and run separately by dedicated teams. The scope, inputs, and interconnections between each model are described below.

The pyrometallurgy model contains the integrated flash furnace, PSCs, WHB, matte granulation and product dryer. Its primary inputs are the concentrate feed and furnace operating targets, from which the model calculates the production of matte and slag. The model outputs the furnace and converter off-gas flowrate, composition and temperature which are fed as inputs to the off-gas model. Furnace cooling requirements and steam production from the WHB are used in the water balance model. The off-gas model includes the furnace and converter hot gas handling systems, WGCP, acid plant and acid coolers. Key outputs from the off-gas model are the gaseous emissions and effluent production. It also calculates requirements of cooling water and make-up water which are used in the water balance model. In addition to requirements from the pyrometallurgy and off-gas models, the water balance model receives site rainfall and evaporation data to determine the total site raw water requirements as it varies across seasons. This involves quantification of the raw, demineralised, and recycled water grades used on site, and variations in cooling requirement between summer and winter months.

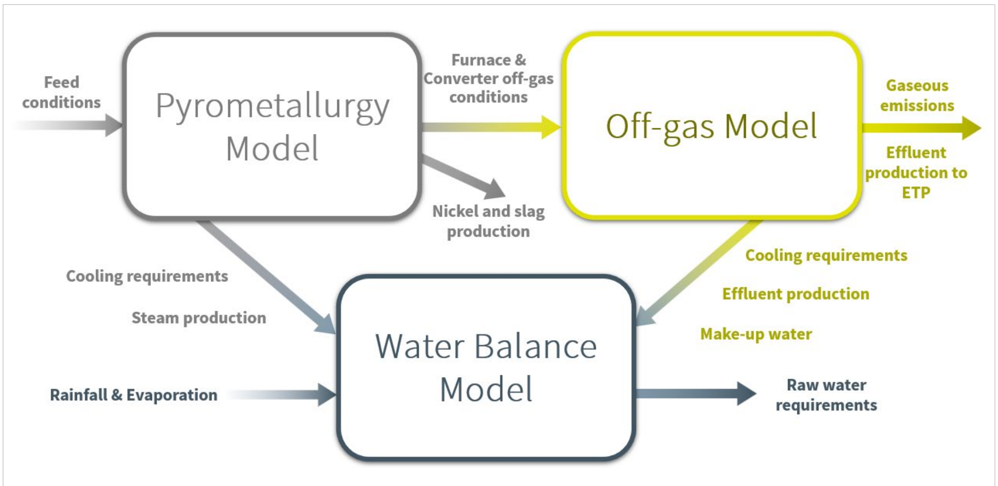

FIG 3 – Interconnection between METSIM models

Being an operating site, calibration of the model was critical to ensure accurate accounting and predictive capability for sensitivity testing of various operating scenarios. A comprehensive set of representative plant data was not always available. In the absence of reliable data from plant instruments, assays or log sheets, secondary sources of data such as existing equipment specifications, benchmarking and previous NKS studies were used to form the calibration basis. For example, the acid plant model was first calibrated to the original equipment manufacturer (OEM) design conditions which included a complete stream table, then validated to a partial set of plant operating data. The calibration process involved comparison of flowrates, temperatures, and compositions of solids, gas, and molten phases, pressures for gas systems, and estimation of heat losses. Critical parameters during calibration included the furnace heat balance and matte composition, PSC cycle times, and extent of SO_2 conversion in the acid plant.

A detailed equipment-level acid plant model had not been developed in METSIM previously. This required various innovations in the modelling approach. Some of the notable challenges in model development are outlined below for the furnace, PSC and acid plant models:

- Due to the complexity of the furnace, it was divided into several blocks to assess the mass and energy balance, matte and slag compositions, and the freeboard and bath reactions at each key stage in the furnace. This included dedicated blocks for the reaction shaft, settler, and uptake shaft.
- The batch converting process had to be adapted to a steady-state model. Each blow of the converting cycle was modelled separately to target a progressively higher nickel grade, while charging additional matte ladles and skimming slag. The 'per blow' flowrates were then converted to an average continuous 'per hour' basis which could then be fed into the continuous furnace and off-gas models.
- Gas pressure drops across equipment and ductwork were manually built into METSIM, as the software does not estimate pressure drops. These pressure drops were correlated to gas flowrate using constant K-factors determined during model calibration.
- Vapour pressure relationships were developed from literature and built into various units in the WGCP and acid plant model. These were used to determine reaction extents for halide removal, conversion of SO_3 to sulphuric acid, and residual water and sulphuric acid in off-gas.
- The acid plant converter beds were modelled using the METSIM Gibbs Free Energy minimisation reactor blocks to calculate chemical equilibrium reaction extents, instead of generic unit blocks used in the majority of the model.

Software Integration

Inputs and outputs between models are shared using a dynamic data exchange (DDE) with Microsoft Excel, providing a streamlined approach to running numerous cases to assess a range of operating scenarios. The Excel interface is used to share inputs between the METSIM models, as well as outputs from FactSage and Arena, as shown in Figure 4. Furnace fluxing relationships derived from FactSage are used to determine the fluxing requirements in METSIM, dependant on furnace operating temperature and concentrate Fe/MgO. The PSC matte charge pattern from Arena defines how many ladles of matte are charged for each blow of the PSC model. A complete set of modelling inputs for each case are listed in Excel, which can be quickly imported into METSIM without the need for manual transcribing. This provides an efficient, centralised and traceable method to run numerous cases with varying inputs.

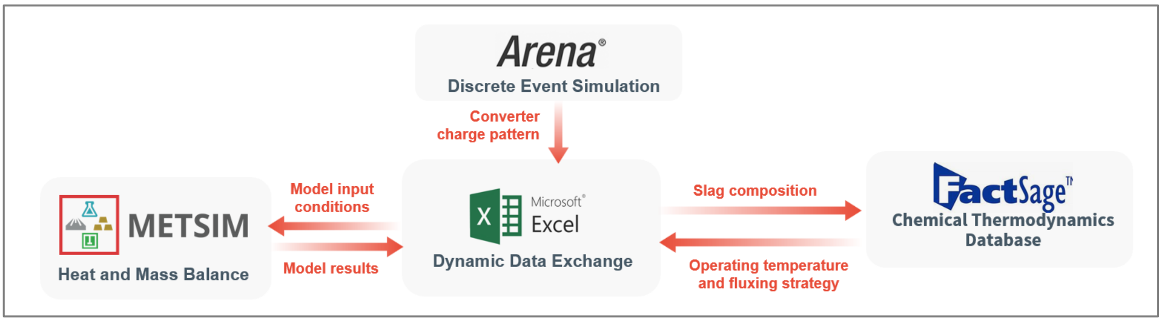

FIG 4 – Modelling Software Integration Diagram

While METSIM was used for the majority of process modelling, additional specialised modelling software was selected for the effluent treatment and power generation areas of the plant. OLI Studio, a thermodynamic software package for aqueous chemistry analysis, was used to model the effluent treatment plant (ETP) and provide reagent consumptions, sludge production and water quality. A Thermoflow model was developed for the steam power system. These packages are more suited to the chemistry and thermodynamics of these areas. These models use METSIM outputs such as steam production and effluent composition to determine equipment sizing and reagent consumption. This approach utilises the strengths of each software, while maintaining an integrated model.

MODEL APPLICATIONS

The Kalgoorlie smelter is dependent on numerous ancillary systems to sustain the furnace operation and meet regulatory requirements. Equipment failure or under-sizing, environmental regulations, or water restrictions may prevent the furnace from reaching its target nickel throughput. Ancillary systems also contribute significantly to capital costs. Therefore, it is critical to assess and design these systems in parallel with primary pyrometallurgical equipment.

Smelter models developed using METSIM are typically focused on pyrometallurgical equipment without integrating off-gas systems, and water balancing at an equipment level. The development of an earlier NKS smelter model in METSIM was discussed by Hunt, Grimsey and Grey (1991). The model scope was limited to the IFF, simplified modelling of PSCs, and some hot gas cleaning equipment (WHB, ESPs, cyclone) for modelling dust recovery. The model was developed prior to the installation of the acid plant and WGCP, and did not include matte granulation and drying, blow-by-blow PSCs modelling, or water balances. A similar modelling approach combining METSIM, FactSage and Arena has previously been documented for the Sudbury nickel smelter (Tripathi et al, 2009). This was also limited to the pyrometallurgical equipment.

The comprehensive and integrated modelling approach developed for NKS can be used to assess individual equipment or the entire modelled flowsheet. Common parameters evaluated include nickel production, consumption rates of flux, oxygen and fuel, off-gas production, water consumption and effluent production. These parameters are assessed under various operating conditions and sensitivities, such as furnace operating temperature, oxygen enrichment, metallurgical targets, changes in concentrate throughput and composition. This provides a broader scope than existing site models, which are specialised to a particular area or equipment.

The modelling results provide a basis for trade-off studies, estimating operating expenditure, and for sizing new equipment. It also assists with sustainability and regulatory assessments by quantifying energy consumption, gaseous emissions including SO_2, carbon intensity, and water consumption. The range of modelled scenarios are used to robustly assess flowsheet capacity and optimise design across a range of metrics including sustainability, processing capacity and costs. This provides greater certainty of the design meeting the site business case.

Furnace Design Application Example

Utilising METSIM model outputs, a finite-volume computational fluid dynamics (CFD) assessment was performed to assess concentrate combustion and understand the flash furnace freeboard gas dynamics. A baseline assessment was performed on the existing furnace geometry, and results were compared to future process and furnace options. This included assessing the transition from four jet-type concentrate burners, to a single dispersion-type burner.

Figure 5 illustrates velocity streamline between the existing furnace and a future process option with a single concentrate burner. Increases in oxygen enrichment and oil burner firing rates were noted to impact the gas dynamics in the reaction shaft (RS), settler, and uptake shaft. Various changes to the furnace geometry (including settler and uptake geometry) were considered and tested using a combination of CFD modelling and industry benchmarking knowledge. The introduction of the single concentrate burner in Figure 5 was found to produce a large-scale upwards recirculation within the reaction shaft. This type of recirculation is common in flash smelting furnaces with a single concentrate burner and has been discussed by White, Gonzales and Anketell (2022).

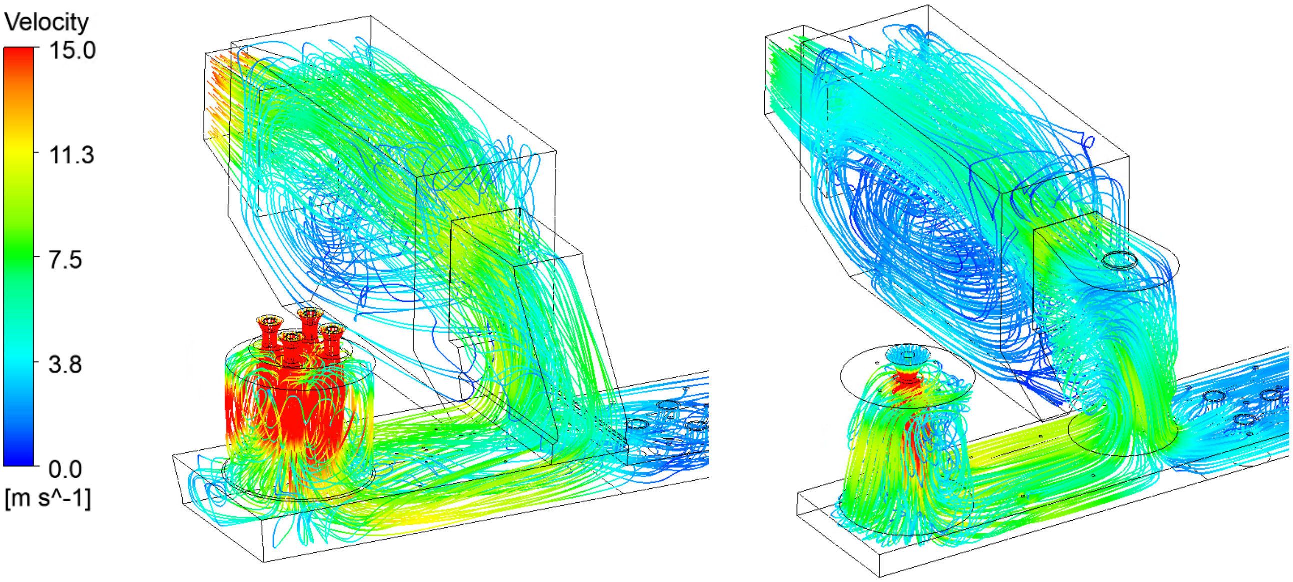

FIG 5 – CFD Velocity Comparison (Left: Existing, Right: Upgrade Option)

For many years Hatch has modelled smelting processes and used process/metallurgical outputs to design furnaces. Across flash smelting and electric smelting, ongoing furnace innovations by Hatch have met challenges of increasingly intensive processes and throughputs. Ongoing improvements in furnace safety, extent of campaign, and improved integrity are the core of Hatch's furnace designs.

Using process outputs (described above), the upgraded smelting process was benchmarked against the smelting industry. The upgraded furnace was evaluated against operating flash furnaces using comparison metrics such as RS residence time, as shown in Figure 6. The figure compares the reaction shaft velocity (m/s) relative to height (m), to understand the residence time to complete concentrate combustion for several cases. The Kalgoorlie upgrade cases for the maximum, nominal, and turndown cases (in addition to high and low Fe/MgO concentrate cases) were evaluated. Further parameters were assessed, including specific smelting intensity (t/h/m^3) and specific energy (MJ/h/m^3).

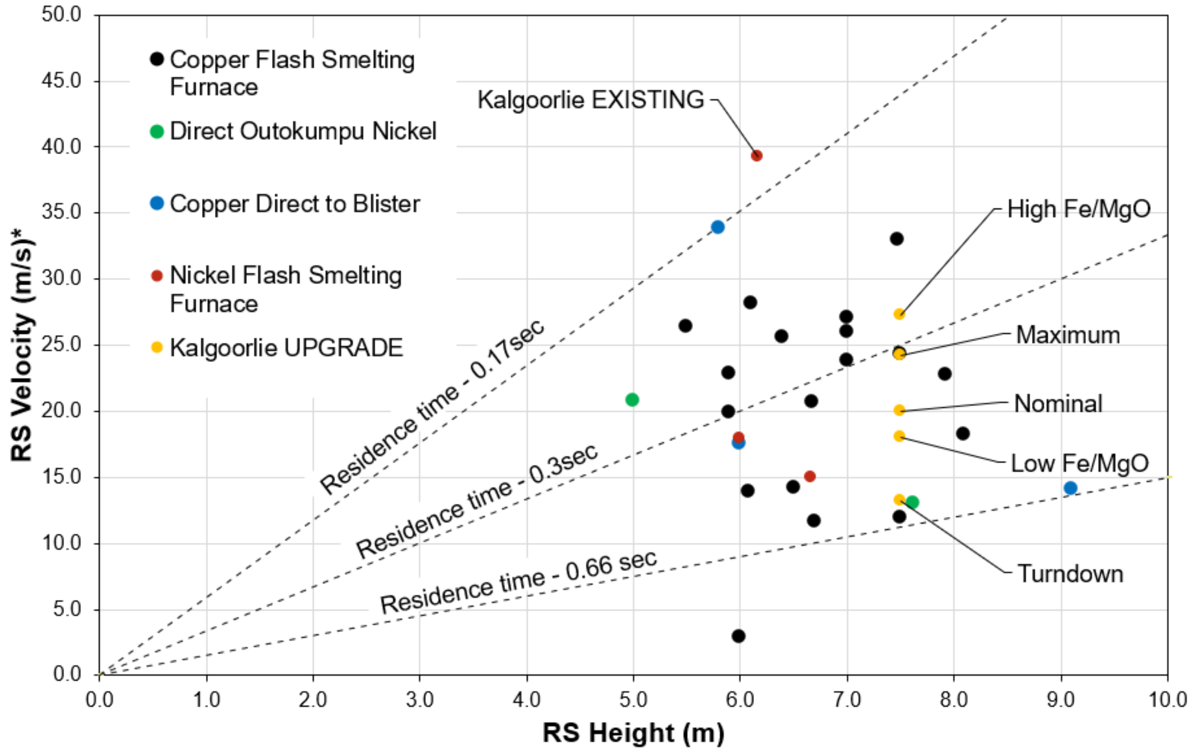

FIG 6 – Furnace reaction shaft residence time

CONCLUSIONS

An in-depth METSIM model has been developed by Hatch with the support of BHP for the Kalgoorlie Nickel Smelter. The interconnected model includes critical off-gas equipment and water balancing, not typically modelled alongside the core pyrometallurgical units. This enables broader flowsheet evaluation and optimisation in preparation for the next smelter rebuild including an investigation of increased throughputs, varying concentrate composition and higher oxygen enrichment to improve energy efficiency. To support the METSIM modelling, FactSage was used to define the fluxing strategy and operating temperature for optimal processing of high magnesia feeds. Arena dynamic simulation of the PSCs and aisle was used to optimise the operation. The specialised modelling packages were integrated through an Excel interface to allow for streamlined simulation of numerous flowsheet options and sensitivity cases. The model results were used for equipment-level assessment across the smelter to define the operating window under future conditions, to quantify emissions and water consumption, and as a key input to the detailed mechanical design of the flash furnace.

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