

Effect of feed composition fluctuations on a platinum furnace energy balance and slag temperature

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In platinum group metals (PGMs) smelting, the slag-to-matte ratios are very high (approximately 4:1 to 9:1). The slag temperature therefore has a strong influence on matte temperature, which is a continual concern due to the low matte melting temperature and its resultant high superheat. Maintaining a stable slag temperature is therefore a critical safety and operational issue. This project aims to improve the understanding of the slag bath temperature drivers so that a more effective slag bath temperature control strategy can be implemented.

With the aim of developing a multiphysics model of the furnace, extensive data analysis was performed to develop an in-depth understanding of the process before the start of modelling work. In this work, the effect of fluctuating furnace feed composition on slag temperature was examined. The results are based on equilibrium calculations using FactSage, implemented with ChemApp.

A method was developed, using an equilibrium calculation at 25°C, to convert the available

chemical assays to approximate mineralogical assays in order to determine the feed enthalpies. Actual 2013 furnace feed data was used and the average specific energy requirement to produce slag and matte at 1600°C was calculated to be 671 kWh/t concentrate. The furnace energy input was then kept constant, and it was found that the slag temperature varies significantly as a function of the feed composition. These results were compared to actual slag temperatures measured on site. It was found that close management of the furnace energy balance is important for maintaining a stable slag temperature.

Introduction

South Africa holds more than 80% of the world's platinum reserves (Nell, 2004). The majority of this platinum is concentrated in two reefs: the Merensky Reef and the UG2 Reef, which contains higher levels of chromite. The ore is mined and processed to produce a concentrate, which is smelted in a furnace to form a matte rich in sulphides and with an increased concentration of platinum group metals (PGMs).

A significant amount of research has been conducted to improve understanding of PGM furnace process conditions. However, not enough is known about the factors that influence slag temperature. It is therefore very difficult to control slag temperature effectively. This means that slag temperature excursions can occur, leading to excessive matte superheat and increased corrosion of the furnace refractory lining. The work presented in this paper is part of a Master's project in the Department of Materials Science and Metallurgical Engineering at the University of Pretoria. The research project is aimed at:

- Identifying the main factors influencing the slag bath temperature
- Developing a qualitative and quantitative understanding of the influences and interactions between these parameters.

The process followed for the research project is shown in Figure 1. It is planned to develop a multiphysics model to investigate the important phenomena in the furnace that affect the slag temperature. A significant amount of focus is placed on developing an in-depth understanding of the process before this modelling commences. One of these phases, the thermochemical analysis, is the focus of this paper. The thermochemical analysis encompasses studies of the effect of changes in chemistry on slag properties and the impact of fluctuations in feed composition on furnace operation. This paper presents the work performed thus far on the effect of concentrate composition fluctuations, based on operational data, on the furnace energy balance.

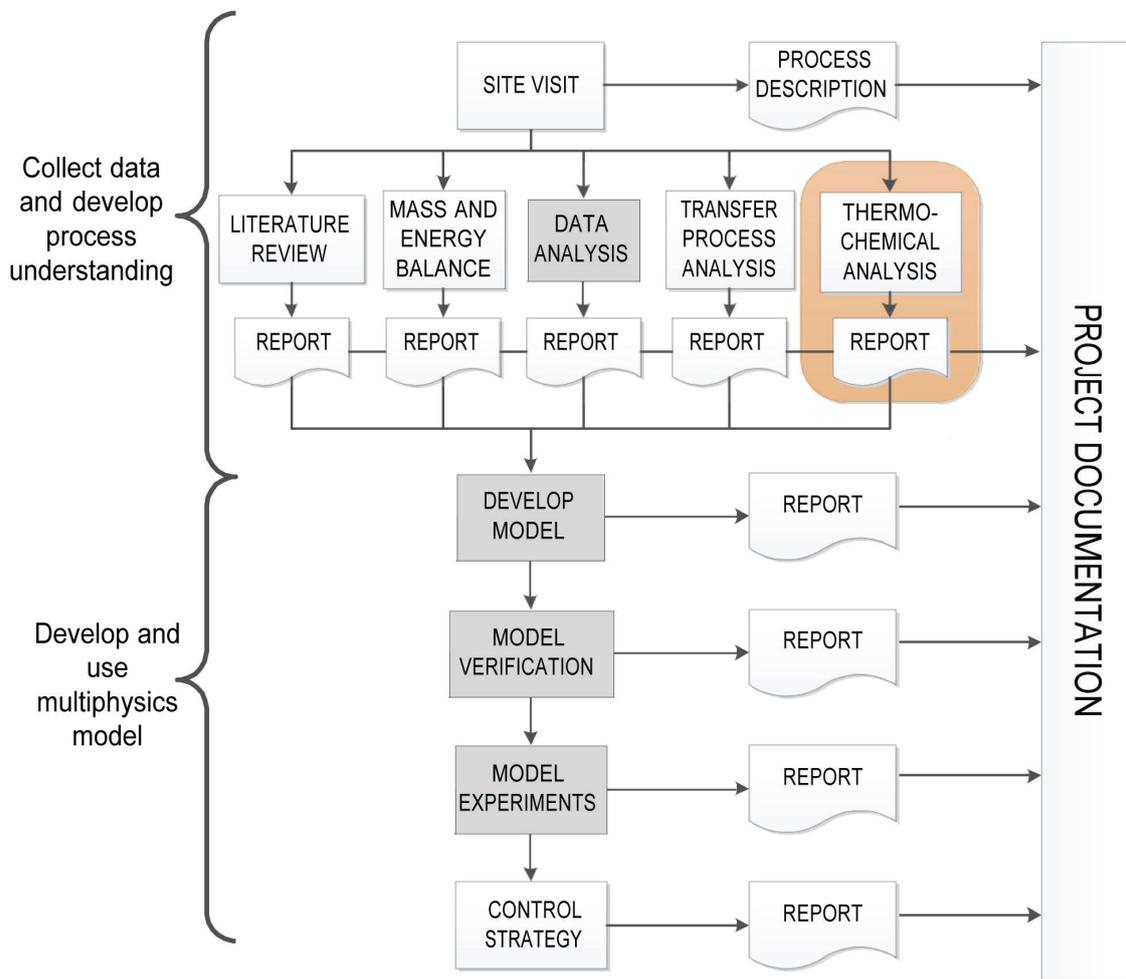


Figure 1. Overall project process to be followed

Process background

Smelting

Concentrate is fed into the smelting furnace, where it forms a layer on top of the slag bath known as the ‘black top’. The matte consists of sulphides of nickel, copper, and iron, which are denser ($SG > 4.5$) than the gangue materials that make up the slag ($3.0 < SG < 3.7$). The sulphides therefore sink to the bottom of the furnace as a matte bath. The Ni, Cu, and Fe sulphides act as collectors for the PGMs.

The electrodes penetrate through the concentrate layer into the slag bath. Some of the electrical current travels through the more conductive matte layer (Bezuidenhout, Eksteen, and Bradshaw 2009). However, it is the current that travels through the highly resistive slag layer that heats the furnace. The matte layer is then heated by thermal conduction and convection from the slag layer.

Importance of the slag

A slag is a molten mix comprised of mainly oxides. The slag originates from the oxide minerals (gangue) that remain in the concentrate after flotation, and from flux additions. Lime can be added as a flux to manipulate the viscosity of the slag.

The slag is a crucial component of the furnace system. Effective management of slag composition is very important to successful furnace operation because:

- The furnace operating temperature is typically a strong function of the slag liquidus temperature. The slag has a higher liquidus temperature than the matte, therefore the furnace is operated with highly superheated matte

- The slag acts as the electrical resistor in the furnace circuit to heat the furnace. It is therefore very important that the slag has a suitable electrical resistivity. The furnace is usually operated with an electrical resistance set-point. The electrode immersion depth will therefore be manipulated as the slag resistivity changes to maintain the furnace resistance. Deeper electrode immersion has been shown to increase slag bath stirring (Ritchie and Eksteen, 2011), which is important to maintain any possible undissolved chromite spinels in suspension so that they do not build up in the furnace
- The slag must have a suitably low viscosity so that the matte droplets can coalesce and settle out through the slag layer to the matte layer. Alumina and silica tend to increase slag viscosity. Slag viscosity is also a strong function of temperature. Lime addition counteracts the effect of high alumina or silica by acting as a flux and lowering the slag liquidus temperature. The slag composition must be managed so that the slag is at a suitable viscosity at the desired operating temperature.

Concentrate blending

The concentrates are supplied from three mines and seven different concentrators. The concentrates are blended together with recycled slurries from the scrubber and slag plant recycle before being dried and fed to the furnace feed bins. A small amount of dust recovered from the off-gas in the electrostatic precipitators is also fed to the furnace.

Samples are taken at regular intervals from a sampling point located below the furnace feed bins. The composite sample for each day is then sent for chemical analysis. The results are reported as Ni, Cu, Cr₂O₃, Fe, FeO, Co, Al₂O₃, MgO, CaO, S, and SiO₂.

Mkhize and Andrews (2011) presented the results of an extensive mineralogical analysis campaign on various PGM concentrates. The minerals marked with an asterisk (*) in Table I were reported to be present in the concentrate in significant amounts. Eksteen (2011) reported similar minerals as being the most abundant in the concentrates.

A mineralogical analysis of slag plant recycle and concentrates from various mines was performed in 2011 (Van Beek 2014). This data was compiled to represent an average feed. The average concentrate blend and slag plant recycle rate for the last five years was used to combine the minerals from the various mines into one average furnace feed. Some similar minerals were grouped together, and those present in low quantities were excluded. Table I shows various minerals that were found in significant amounts. Approximately 2.5% of the feed was omitted due to the concentrations of the numerous minerals being too low to be considered significant. As there was no data available for the sodium content of the feed, plagioclase (approximately 7% of the blend) was removed from the assay before it was normalized. Olivine is found in the furnace feed, but not in the concentrate. It enters the feed as slag plant recycle material.

Table I. Abundant minerals of a typical furnace feed

Mineral	Chemical formula
Ore minerals	
Pentlandite*	(Fe,Ni,Co) ₉ S ₈
Chalcopyrite*	CuFeS ₂
Pyrrhotite*	Fe _{1-x} S _x
Pyrite*	FeS ₂
Gangue minerals	
Pyroxenes*	(Mg,Fe)SiO ₃ -Ca(Mg,Fe)Si ₂ O ₆
Plagioclase/feldspar*	NaAlSi ₃ O ₈ -CaAl ₂ Si ₂ O ₈
Alteration silicates*	Hydrated minerals
Chromite*	FeCr ₂ O ₄
Olivine	(Mg,Fe) ₂ SiO ₄
Quartz	SiO ₂
Haematite	Fe ₂ O ₃

* Major constituents (Mkhize and Andrews, 2011)

Method

An investigation was conducted to determine the effect of furnace feed fluctuations on the energy balance and whether this could have a significant effect on furnace slag temperature. FactSage version 6.4 (Bale *et al.*, 2009) data was used to perform the equilibrium calculations, and the calculations were automated using ChemApp version 6.3.4 (GTT-Technologies, 2003) and Python version 3.3 (Van Rossum, 2014).

Site data for 2013 was used as the basis of the investigation. The daily average data for concentrate composition, lime addition, furnace power, and slag temperature was used. The periods where data was missing, or the furnace was down or operating on low power were removed. Dates with chemical assays summing to more than 108% or less than 92% were also removed, as these assays are most likely unreliable. This left 219 days' data for analysis.

The first step was to convert the available chemical assays to mineralogical assays so that an accurate feed enthalpy could be calculated. The second step was to calculate the energy required to smelt the various feed mixes for 2013. The third step investigated the effect of feed fluctuations on slag temperature, assuming that a constant energy input per ton of concentrate was maintained for the year. Figure 2 shows the steps followed in the analysis.

Feed mineralogy reconciliation

Gibbs free energy minimization can be used to calculate the equilibrium state of a chemical assay at 25°C. This will produce an estimate of the mineralogical assay. The chemical assays determine only metal and sulphur contents. Oxygen and hydrogen are not recorded, and these need to be input to the equilibrium calculation in the correct amounts to obtain an accurate mineralogy.

The chemical assays assume that all of the iron is present as FeO; however, the mineralogy shown in Table I suggests that this is not the case. It is most likely that Al, Cr, Mg, Ca, and Si are present in an oxidized state. The oxidation state of the base metals (Ni, Fe, and Co), is uncertain. There are also hydrated minerals (containing bound water) present in the feed that are not accounted for in the chemical analysis.

The ratio of base metals to base metal oxides and the bound water content of the concentrate were therefore the two parameters used to manipulate the mineralogical assay. Various chemical assays were allowed to equilibrate at 25°C with different base metal to base metal oxide ratios and amounts of water addition. These results were then compared to the known mineralogy.

A number of phases that are unlikely to be present were excluded from the calculation. This decreased the computation time and improved the quality of the results.

Energy balance calculations

The concentrate for each day of the 2013 data-set was equilibrated at 25°C, with a fixed base metal to base metal oxide ratio and water addition. It was assumed that these values remained constant for the year, as insufficient mineralogical data was available to determine if they vary. The enthalpies of the concentrate on a chemical basis and a mineralogical basis were recorded. The lime as per operational records was added and this mixture was equilibrated at 1600°C, the desired operational slag temperature. The energy balance was then calculated. This was performed for each day of 2013 for which reliable data was available.

The average smelting energy requirement was calculated for 2013. A second program was used to calculate the theoretical slag temperature for each day at this fixed energy input to the concentrate, assuming that all other operating parameters remain the same. This demonstrated the effect of varying feed composition on slag temperature based on actual historical data.

Figure 2 shows the calculation steps followed in this study.

Results and discussion

Feed mineralogy

The available mineralogical assay was compared to the calculated mineralogy for chemical assays from November 2013 for different base metal to base metal oxide ratios and water additions. The comparison is limited because the chemical assay was not available for the time at which the mineralogy study was conducted, therefore a direct comparison cannot be made.

The water addition was found to directly affect the amount of talc ($\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$) and calcium amphibole ($\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$) that formed. These were equated to alteration silicates in the actual assay. The talc and calcium amphibole abundances were found to be optimum at 0.6% water addition.

The ratio of base metals to base metal oxides was found to affect a number of factors; however, a reasonable value was found to be 0.5. Low haematite contents are present in the calculated and measured assays. The quartz and chalcopyrite contents at equilibrium are seen to vary, although they are similar to the measured values. The olivine content of the calculated assay varies significantly; however, on average it is comparable to the measured value. The calculated pyroxene and pyrrhotite contents were lower than in reality. This is because at the equilibrium state a significant amount of iron occurs in the two spinel phases, which together constitute a much higher amount than the actual chromite. The pyrite and pentlandite amounts compare well. Figure 3 shows the results for October 2013 at these values.

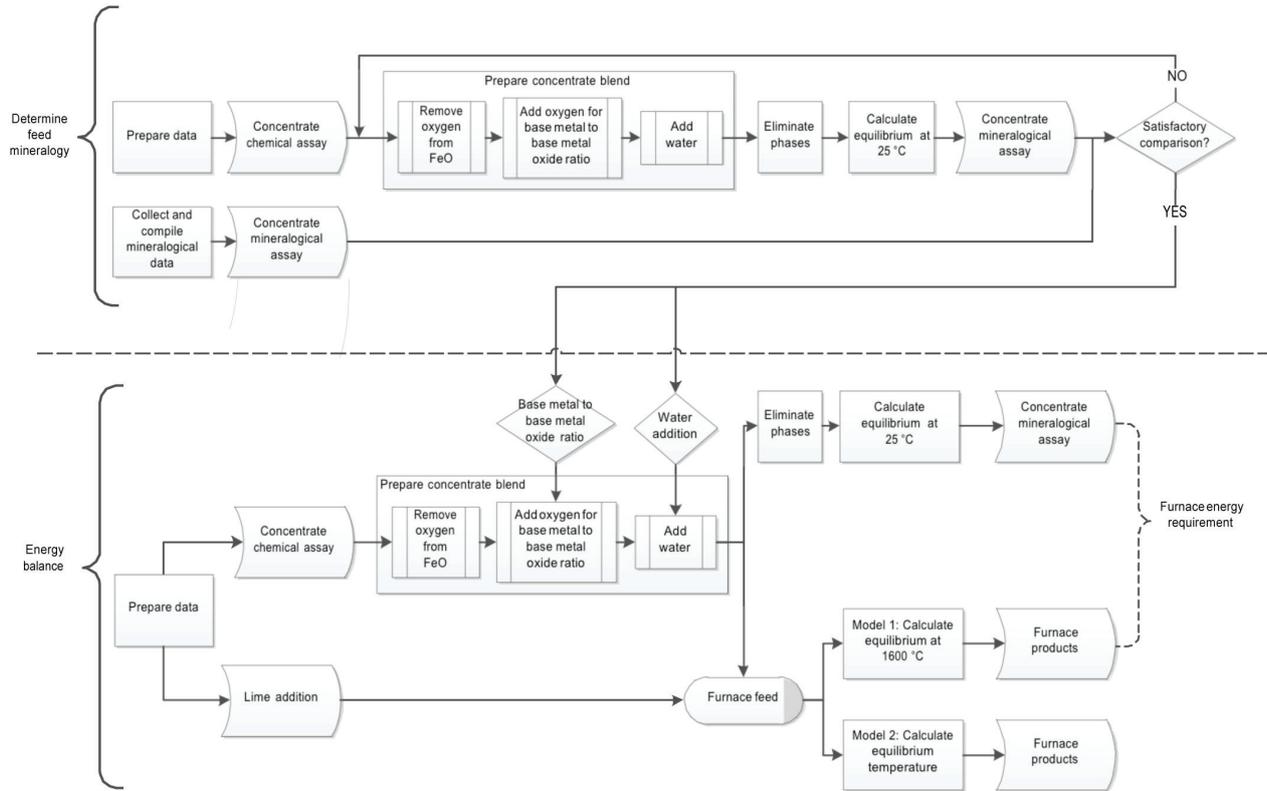


Figure 2. Calculation steps followed in the analysis

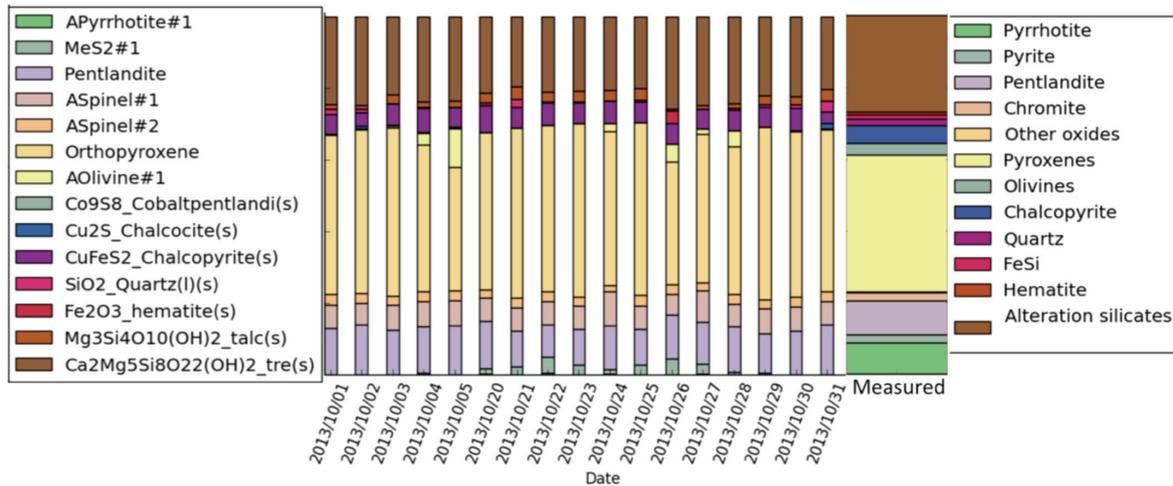


Figure 3. Mineralogy calculated by FactSage for November 2013 (left), compared to mineralogy as measured in 2011 (right)

The enthalpy of the feed in chemical form was calculated for comparison to determine the potential error in using the chemical assay directly in an energy balance. All iron was assumed to be FeO for this analysis (as it is reported in the chemical analyses available). The average concentrate enthalpy difference between the chemical and mineralogical assays was found to be 375 kWh/t for November 2013. This is more than half of the furnace energy requirement (Figure 4). The importance of using an accurate mineralogical assay in energy balance calculations is clearly illustrated.

Effect of concentrate fluctuations

Figure 4 shows the theoretical daily energy requirement for 2013. This was calculated to obtain a product temperature of 1600°C. There are some missing data points, as described previously. The average energy requirement for 2013 was found to be 671.1 kWh/t. The actual energy input to the furnace, or specific energy requirement (SEC) per ton concentrate, ranges from 700 to 800 kWh/t. The SEC is higher than the theoretical energy requirement because of heat losses.

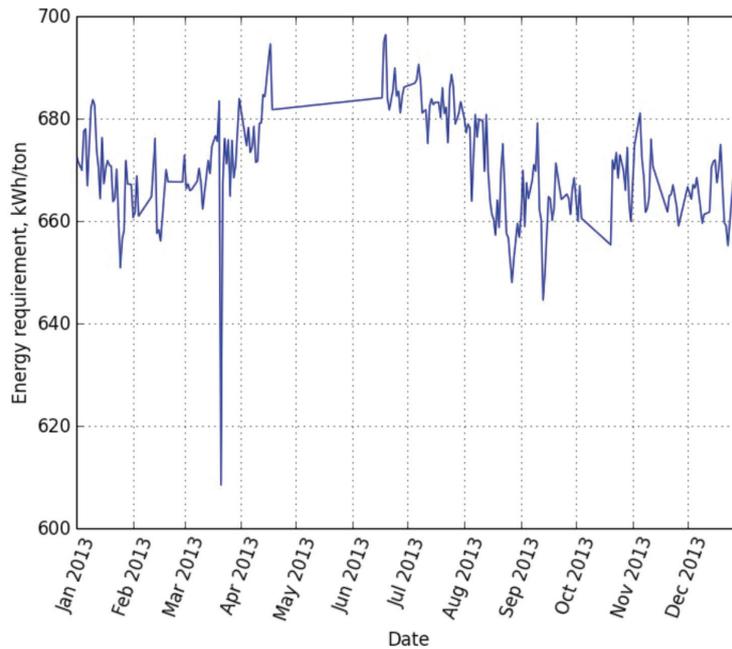


Figure 4. Theoretical energy requirements for 2013

Figure 5 shows the theoretical slag temperature fluctuations for 2013. It was assumed that slag temperature is influenced only by the concentrate chemistry and that a constant energy input of 671.1 kWh/t was maintained. The average daily slag temperature, as measured by a pyrometer when the slag is tapped, is also shown for comparison.

The significant outlier in the calculated slag temperature on 21 March 2013 is due to a high iron content in the chemical assay. This is most likely a result of measurement error.

The desired slag temperature is 1600°C. The maximum safe operating slag temperature for short excursions is 1640°C. If the slag temperature rises above this, refractory wear is likely to increase.

On average, and especially in July after start-up, the measured slag temperature was higher than expected. However, it does appear that on certain days the measured and theoretical slag temperatures correlate quite closely temperatures for 2013.

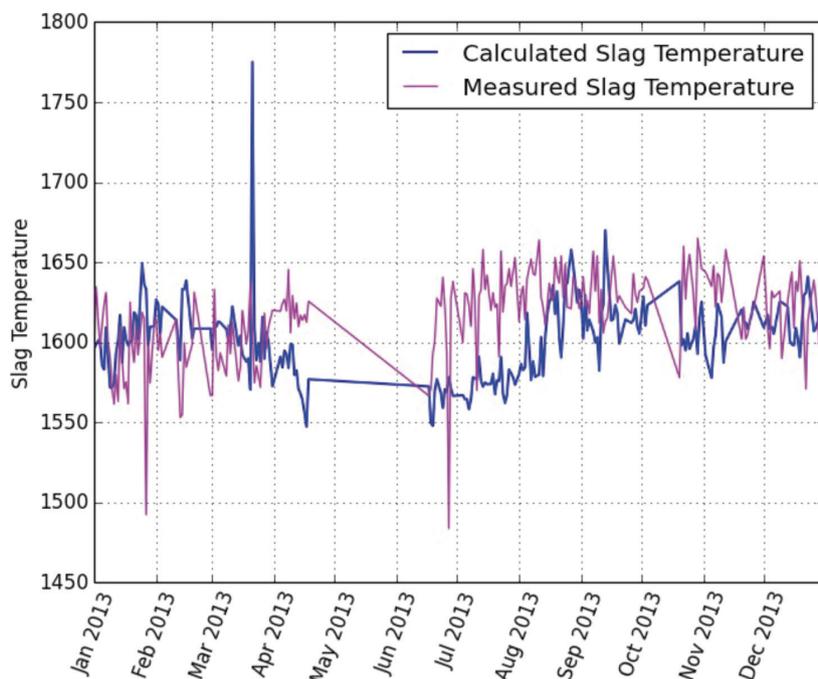


Figure 5. Calculated and measured slag

Conclusions and recommendations

An understanding the mineralogy of the feed to PGM smelting is important as it has a significant effect on the energy balance. A simple method was developed for approximating the feed mineralogy from a given chemical assay. Some limitations of this method were identified, however, and the accuracy of calculated mineralogy could not be fully quantified because a chemical analysis of the mineralogical samples was not available. The effect of using a chemical assay instead of a mineralogical analysis in the furnace energy balance was shown to be significant. The difference between the enthalpy of this mineralogical assay and the chemical assay with iron as FeO was found to be 375 kWh/t concentrate on average for November 2013.

These results show that the feed enthalpy does vary from day to day and this can have an effect on slag temperature. Figure 5 shows that the effect of fluctuations in feed chemistry on slag temperature is most likely not negligible. It is therefore critical to manage the furnace energy balance so that a consistent slag temperature can be maintained. The current feedback method used to control the SEC based on concentrate bed depth appears to be insufficient to dampen all the effects of the concentrate fluctuations. The actual slag temperature is often higher than the calculated slag temperature; it is therefore likely that there are other factors, apart from the fluctuations in concentrate composition, influencing the slag temperature.

The effect of the changes in feed composition on slag properties has not been quantified in this study, and this will be the next step in the thermochemical analysis of the furnace slag. The fluctuations in chemical composition will affect slag liquidus temperature, viscosity, and resistivity. This needs to be investigated further.

The accuracy of the calculations presented is strongly dependent on the concentrate mineralogy and associated feed enthalpy. The only mineralogical data available is from 2011. Updated mineralogical analyses could be performed, as well as loss-on-ignition tests, to more accurately determine the crystal water content of the concentrate. This would help to improve the accuracy of the energy balance.

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Nicole completed her BEng in chemical engineering with distinction at the University of Pretoria in 2011. She worked as a junior process engineer at Resonant Environmental Technologies from 2012 to 2013. She was involved in numerous projects related to smelter offgas cleaning, secondary fume extraction and energy recovery from furnace offgas in South Africa and abroad. During this time she also completed her Honours in Chemical Engineering at the University of Pretoria, with a focus on optimisation and energy generation. She then decided to return full-time to the academic environment and enrolled in January 2014 for a Masters in Metallurgical Engineering at the University of Pretoria co-supervised by Dr Johan Zietsman and Dr Axel Lexmond.



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Burger van Beek started as an Engineer in training at the old Iscor Vanderbijlpark in 1996. He enjoyed the Pyrometallurgical challenges of the Steelmaking process and gained operational experience in Secondary Metallurgy. In 2002 Burger van Beek moved to the PGM smelting industry and held various positions at the Lonmin Smelter. Settling in the role of Process Manager, Burger van Beek gained experience in the operational and design aspects of PGM smelting furnaces. Experience was also gained in terms of best practices in metal accounting and process control and monitoring. In 2014 Burger van Beek took up the role of Process Specialist focusing on the long term strategy and development of the Smelting operation.



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