Design, Construction and Performance of the Copper Cooling System Installed in the First ISACONVERT™ Copper Converting Furnace

Conference Paper · September 2023

5 authors, including:

Hugo Joubert
Tenova Pyromet
14 PUBLICATIONS **20** CITATIONS
SEE PROFILE

Isobel Mc Dougall
Tenova Pyromet
13 PUBLICATIONS **41** CITATIONS
SEE PROFILE

Stanko Nikolic
Glencore Australia Holdings
29 PUBLICATIONS **318** CITATIONS
SEE PROFILE

Design, Construction and Performance of the Copper Cooling System Installed in the First ISACONVERT™ Copper Converting Furnace

Joubert, H., Tenova Pyromet, Midrand, South Africa

Mc Dougall, I., Tenova Pyromet, Midrand, South Africa

De Villiers, G., Tenova Pyromet, Midrand, South Africa

Nikolic, S., Glencore Technology, Brisbane, Australia

Dyussekenov, N., First Quantum Minerals, Ravensthorpe, Australia

Eggert, M., Kansanshi Mining Plc, Kansanshi, Zambia

Abstract

The first ISACONVERT™ copper converting furnace was commissioned at Kansanshi Mining Plc in 2019 and a number of successful operating campaigns have been completed since. The furnace was built to operate as a demonstration unit prior to entering full production duty for the site. Industry experience indicated that an aggressive slag combined with a high sidewall heat load would be likely and so Glencore Technology contracted Tenova Pyromet to design and supply a copper cooling system for the slag bath sidewall. Tenova Pyromet selected its high intensity MAXICOOL® copper cooling system due to the expected operating temperatures and sidewall heat loads. The hot face of each cooling element was initially coated with a sacrificial monolithic refractory layer. To date no wear has been detected on the MAXICOOL® copper coolers and a stable slag freeze lining is maintained on the hot face of the cooling elements. In this paper, we review the design of the copper cooling system, its installation, and its performance during the initial campaigns. In particular, we compare the measured operating heat fluxes and cooling element temperatures to those calculated during the design phase. Finally, we explore potential improvements for future installations.

Keywords: Converting, Top submerged lance furnace, ISACONVERT™, Copper cooling, Freeze lining, Heat transfer, MAXICOOL®

1. Introduction

The Kansanshi Copper Smelter located near Solwezi in Zambia was commissioned in March 2015. The smelter is a sub-division of Kansanshi Mining Plc (KMP), which in turn is 80% owned by First Quantum Minerals Ltd. (FQML) and the remaining 20% by ZCCM Investments Holdings Plc. At the time of start-up, the smelter complex comprised a primary smelting ISASMELT™ top submerged lance furnace, a matte settling electric furnace, four Peirce Smith converters, two anode furnaces, two anode casting wheels, an oxygen plant and an acid plant. The flowsheet for the Kansashi Copper Smelter as at start-up is shown in Figure 1. The smelter ramp-up was faster than anticipated, and commercial production was reached by July 2015, six months ahead of schedule (De Vries, Hunt & Hanshar, 2016). By 2019 the smelter consistently operated at a copper concentrate throughput rate of 1.38 million tonnes per annum, well above nameplate capacity of 1.2 million tonnes per annum (Hunt & De Vries, 2019) and in the following years kept exceeding that benchmark.

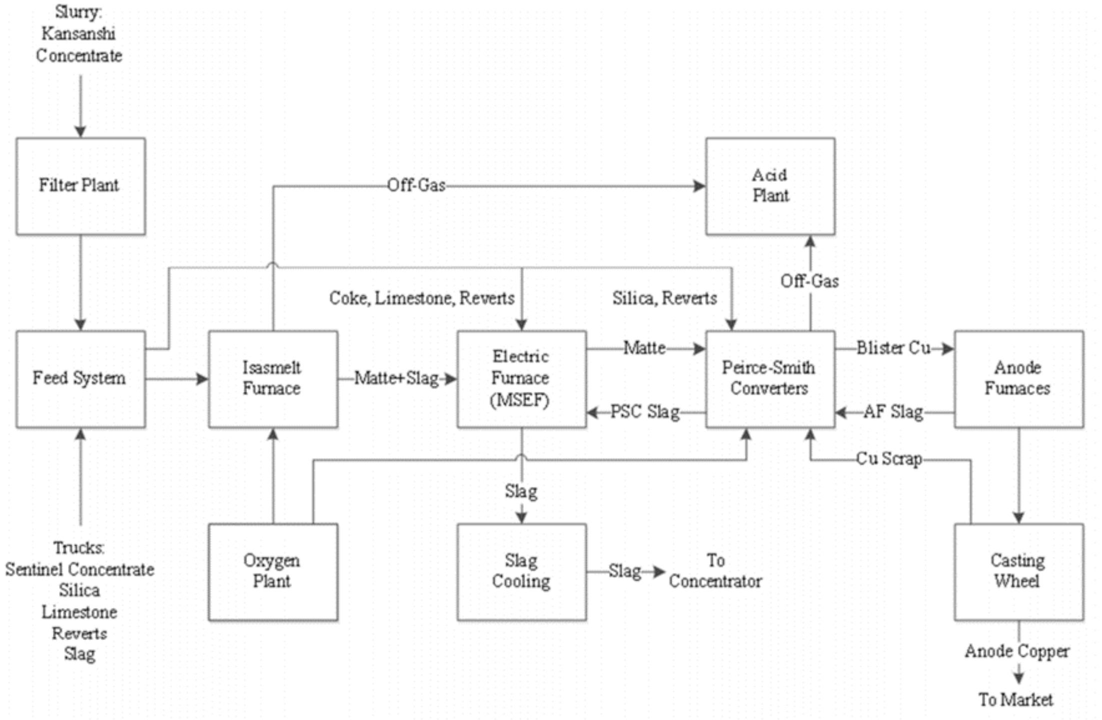

Figure 1: Flowsheet for the Kansanshi Copper Smelter (De Vries, Hunt & Hanshar, 2016).

Even before the successful start-up of the Kansanshi Copper Smelter, KMP commenced enquiries regarding a potential future smelter expansion. As part of the smelter expansion KMP decided to install an ISACONVERT™ continuous converting furnace. Continuous converting technology has potential environmental benefits due to improved off gas capture and a more stable SO_2 concentration in the off gas stream. In 2013 KMP awarded the contract to Xstrata Technology (now Glencore Technology) for the design and supply of a commercial scale ISACONVERT™ furnace. The ISACONVERT™ furnace is a top submerged lance furnace technology marketed and supplied by Glencore Technology and based on the successful ISASMELT™ primary smelting furnace technology. The KMP ISACONVERT™ furnace was commissioned during 2019 and is designed to nominally treat 12 t/h of solid, crushed matte at 60-64 wt% Cu, producing 80,000 tpa of blister copper.

A lime-ferrite slag system is used for the continuous converting of copper in the ISACONVERT™ furnace. Due to the aggressive nature of the slag, the sidewall design adjacent to the slag bath requires the use of water-cooled copper to establish and operate with a protective slag freeze lining (Edwards & Alvear, 2007). Since 2007, Glencore Technology has been working with Tenova Pyromet to develop a suitable copper cooling system for the ISACONVERT™ furnace slag sidewall. The copper cooling system makes use of Tenova Pyromet's high intensity MAXICOOL® copper coolers to establish and maintain a competent freeze lining adjacent to the agitated and aggressive slag bath. Tenova Pyromet has extensive experience in the design and supply of sidewall copper cooling systems for base metal furnaces (Joubert, Nikolic, Bakker & Mc Dougall, 2016).

This paper reviews the ISACONVERT™ furnace slag sidewall lining and cooling system design, including its site installation. Feedback is provided on the first operating campaign and the actual operating and slag bath conditions experienced. The performance of the MAXICOOL® copper coolers is discussed, including the heat fluxes and cooler temperatures recorded. The actual cooler performance is compared to the original design calculations. Thermal finite element analysis is used to reconcile the actual performance values to the original design and re-evaluate the slag bath to freeze lining hot face heat transfer coefficient.

2. Copper Cooling System Design

The ISACONVERT™ copper converting furnace is a top submerged lance furnace. An illustration of the KMP ISACONVERT™ furnace is shown in Figure 2. It consists of two main sections: the lower cylindrical barrel section containing the metal and slag bath and the upper freeboard or so-called kettle section. The sidewall copper cooling system covers the furnace barrel sidewall zones that will be directly exposed to the aggressive calcium-ferrite slag bath. As illustrated in Figure 2, the copper coolers are arranged in three separate rings on different levels. The bottom cooler ring is the lowest and extends down into the slag-blister tidal zone. Each cooler ring consists of eight copper coolers. A lap joint prevents superheated slag from leaking through the interface between adjacent coolers.

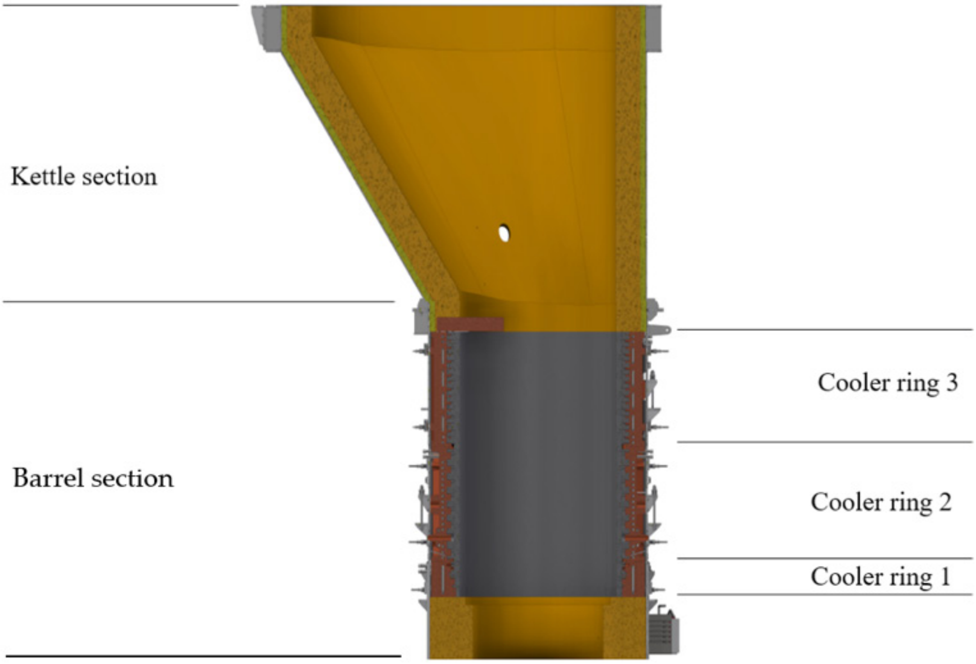

Figure 2: Elevation section through the KMP ISACONVERTTM copper converting furnace.

2.1 Intensively Cooled Sidewall

The sidewall heat flux adjacent to the slag bath on operating primary copper smelting ISASMELT™ furnaces typically ranges between 3 and 6 kW/m^2, depending on the remaining sidewall refractory lining thickness. The corresponding slag bath to lining hot face convective heat transfer coefficient ranges between 600 and 1000 W/m^2K. This is a high heat transfer coefficient compared to most other furnace operations and is driven by the turbulent nature of the top submerged lance furnace slag bath (Joubert, Mc Dougall & De Villiers, 2019). The bath to lining hot face heat transfer coefficient for the ISACONVERT™ furnace was assumed to be in a similar range as for a typical ISASMELT™ furnace due to the same turbulent bath conditions. However, in contrast to a typical ISASMELT™, the ISACONVERT™ furnace lining/cooling is designed to operate with a slag freeze lining throughout its campaign life. This is due to the aggressive nature of the lime-ferrite slag that is likely to result in a high wear rate of a refractory only lining (Edwards et al., 2007). Once a slag freeze lining has been established and maintained, the heat flux through the sidewall will be equal to the product of the slag bath to lining hot face heat transfer coefficient and the slag bath superheat as per Equation (1) (Joubert & Mc Dougall, 2019).

$$q_{in} = h_{bath}\Delta T = h_{bath}\left(T_{bath} - T_{freezing}\right) \qquad 1)$$

where q_{in} = heat flux (kW/m^2)

h_{bath} = bath to sidewall/freeze lining heat transfer coefficient (W/m^{2}K)

T_{bath} = bath temperature (K or °C)

$T_{freezing}$ = estimated slag freezing temperature (K or °C)

By combining the high heat transfer coefficient of 1000 W/m^{2}K with a slag superheat of up to 80°C anticipated for the ISACONVERT™ furnace, an operating heat flux of up to 80 kW/m^2 was estimated. Considering this high estimated operating heat load combined with the uncertainty surrounding the actual operating conditions of a full scale ISACONVERT™ furnace, it was decided to incorporate a high intensity copper cooling system in the furnace bath sidewall. Tenova Pyromet's MAXICOOL® high intensity copper sidewall coolers were selected based on their successful use in a PGM slag cleaning furnace containing a high superheat aggressive fayalitic slag (Joubert, Nourse, Masters & Hundermark, 2005).

The MAXICOOL® coolers are high intensity sidewall copper coolers of the waffle or stave type. They consist of cast copper of high purity and conductivity with cast-in monel piping forming the cooling water circuits. A unique star pattern is used for the hot face of the coolers to provide support initially for the castable refractory, and later on for the frozen slag layer, whilst limiting thermal stress transmitted to the base of the cooler. Two cooling water circuits are used per cooler, which run in parallel through the copper cooler, each designed to carry the maximum heat load of the individual cooler. The manufactured MAXICOOL® copper coolers for the KMP ISACONVERT™ furnace are shown in Figure 3. The three pre-assembled cooler rings are shown on the right in Figure 3.

Figure 3: The KMP ISACONVERT™ MAXICOOL® Copper Coolers.

2.2 Construction

As per the original plan, only the top two cooler rings (Rings 2 & 3) were installed for the first furnace campaign. The Ring 1 coolers were to be installed from the second campaign onwards depending on the actual blister copper operating levels achieved during the first campaign. No coolers are to be installed below the blister copper level as it likely to damage the coolers and potentially cause water leaks inside the furnace. The Ring 1 cooler height is significantly lower than that for the Ring 2 & 3 coolers to allow for this critical adjustment in overall sidewall cooler height relative to the blister copper operating level.

Each of the MAXICOOL® copper coolers is attached to the furnace shell using spring loaded connections. It incorporates a sliding joint to allow for vertical movement relative to the furnace shell. The vertical movement is likely due to hearth and lower sidewall refractory expansion and contraction. A spring loaded hold down mechanism ensures the coolers are pulled downwards during a furnace cooling down period to prevent horizontal gaps opening up between the coolers and the refractory lining below, as well as between the cooler rows. Each cooler has two inlet and two outlet cooling water connections for the two parallel running cooling water circuits. The cooler spring loaded connection, hold down mechanism and cooling water connections are shown in Figure 4.

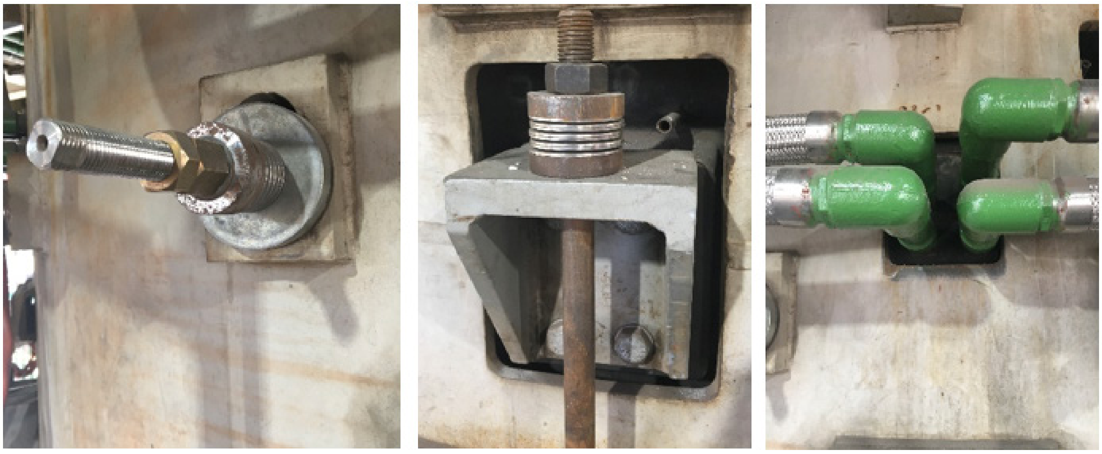

Figure 4: MAXICOOL® cooler shell connection, hold down mechanism and cooling water connections.

A sacrificial layer of high alumina monolithic refractory was cast onto the hot face of each cooler. The refractory was cast and dried on site prior to installation. Each MAXICOOL® copper cooler has three imbedded thermocouples to monitor the hot face copper temperature in front of the cooling water channels during operation. One thermocouple is located close to the bottom of the cooler, one slightly above the centre height of the cooler, and one at the top of the cooler. The thermocouples are located 15 mm from the hot face of the cooler main body, behind the hot face retention stars. A cooler with the pre-cast refractory is shown in Figure 5, as well as a typical copper thermocouple installation. The cooler installation was completed in June 2019.

Figure 5: MAXICOOL® cooler with sacrificial refractory layer and typical copper thermocouple installation

3. ISACONVERT™ Operation

3.1 Plant Operation

In mid-2019, the commissioning and first operating campaign of the ISACONVERT™ furnace was completed at the Kansanshi Copper Smelter. Between 2019 and 2021, the ISACONVERT™ furnace was operated in four campaigns, separated by site requirements such as shutdowns or COVID-19 lockdowns, in which the matte treatment rate steadily increased from an average of 35 tonnes per day to an average of 245 tonnes per day (Eggert, Dyussekenov, Chirwa & Hogg, 2022). No refractory relining or modifications were made to the furnace or the coolers during this period, with some changes made to the tapping systems as detailed by Mwanza et al (2022).

3.2 Operating Parameters & Slag Properties

In industrial practice, selection of operating conditions for a copper converting furnace focuses on blister quality, most notably the sulfur concentration, to optimise the cycle time of the subsequent fire refining vessels. The sulfur concentration in the blister is controlled by the oxidation state of the system and this therefore sets a corresponding equilibrium concentration of copper oxide in slag. Copper oxide lowers the liquidus temperature of the slag, and hence an increase in oxidation state results in an increase of the slag superheat independent of temperature. The second lever for controlling slag superheat is the target fluxing Fe/CaO ratio for the slag which is used to control the solubility of the primary phase, normally magnetite (spinel), and hence slag superheat.

The control of the selected Fe/CaO ratio and the copper oxide concentration in the slag can be achieved through effective mass balancing of the system by accurately measuring and controlling oxygen inputs, and feed flow rates and compositions. Fundamental data, from Nikolic et al (2008 & 2009), was used to define the impact of these parameters on slag superheat, at fixed copper oxide concentrations, as shown in Figure 6. The diagram enables the operating window for the slag composition to readily be identified. The bounding primary phase fields are dicalcium ferrite (2CaO.Fe_2O_3) and spinel/magnetite (Fe_3O_4) below which the slag is no longer superheated. At 1250°C and an oxidation state resulting in 20wt% Cu_2O in slag, for example, the slags are superheated in the Fe/CaO wt/wt ratio range between 1.7 and 3.0. However, at 10wt% Cu_2O the range of superheated slag reduces to Fe/CaO wt ratio between 2.0 and 2.8. This information, combined with typical plant variability seen in the inputs in industrial ISASMELT™ plants, was used to calculate appropriate ranges for the slag superheat to be used for the design process of the copper cooling system.

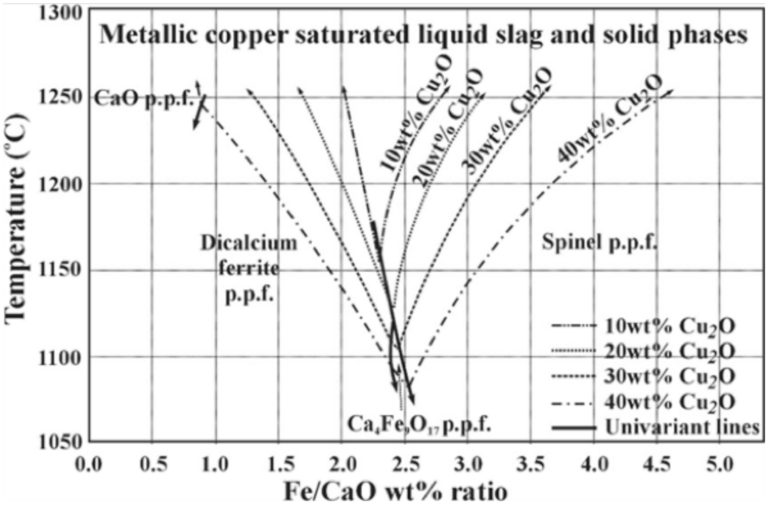

Figure 6: Liquidus temperatures in the "Cu_2O"-FeO-Fe_2O_3-CaO system in equilibrium with copper metal represented as Fe/CaO wt% ratio at different Cu_2O concentrations in liquid (Nikolic et al 2008 & 2009).

4. Copper Cooler Performance

4.1 Anticipated Operating Conditions and Performance

A number of potential operating load cases were identified during the cooler design phase. For each load case a set of boundary conditions was identified that were used to evaluate the sidewall lining/cooling system design (Mc Dougall, 2014). The load cases and associated boundary conditions are listed in Table 1. The design slag bath operating temperature range was selected based on the fundamental research previously referenced (Nikolic et al 2008 & 2009) and from ISACONVERT™ copper converting pilot scale test work (Edwards & Jahanshahi 1999). The bath to sidewall heat transfer coefficient is high due to the turbulent nature of the top submerged lance furnace bath, and the range selected is in line with heat transfer coefficients calculated based on measured heat fluxes on copper ISASMELT™ furnaces (Joubert, Mc Dougall & De Villiers, 2019). The freeze lining thicknesses and thermal conductivity was an estimate at the time for evaluation purposes.

Table 1: Slag bath zone operating & boundary conditions

Boundary condition/ material property	Units	Load Case		
		Normal	Extreme 1	Extreme 2
Bath temperature	°C	1,240	1,350	1,350
Bath-to-sidewall heat transfer coefficient	W/m^2K	200	1000	1000
Cooling water temperature	°C	35	35	35
Cooling water heat transfer coefficient	W/m^2K	7,000	7,000	7,000
Slag freeze lining thickness (assumed)	mm	30	10	0
Slag freeze lining conductivity	W/mK	1.8	1.8	1.8

The cooler design was evaluated prior to implementation using thermal finite element analysis (FEA) modelling for the load cases listed in Table 1. The FEA results for a typical Row 2 cooler, fully exposed to the slag bath, are listed in Table 2. The calculated hot face heat flux, maximum copper temperature, and the copper temperatures at the three copper hot face thermocouple locations are listed.

Table 2: Thermal FEA results for typical Row 2 cooler

Parameter calculated	Units	Load Case		
		Normal	Extreme 1	Extreme 2
Heat flux	kW/m^2	52	160	900
Maximum hot face copper temperature	°C	96	198	397
Bottom copper thermocouple temperature	°C	43	59	115
Middle copper thermocouple temperature	°C	43	59	101
Top copper thermocouple temperature	°C	40	53	96

Based on the FEA results the cooler design was deemed capable of removing the excess heat from the bath and ensuring that a protective slag freeze lining will be formed and maintained, even under the extreme operating conditions considered. Extreme condition 2 is in fact an instantaneous condition evaluated as a steady state condition, maintained for an indefinite period of time. In reality a freeze lining will immediately start to form, reducing the heat flux and copper operating temperatures. As such it represents an unrealistic worst case. Nonetheless, even under these conditions, the maximum copper temperature is maintained below 400°C, which is considered by the designers as a design limit to prevent copper oxidation and ensure that the cooler structural integrity is maintained (Joubert et al., 2019).

4.2 Actual performance

During all the operating campaigns to date a stable slag freeze lining has been formed and maintained on the hot face of the MAXICOOL® coolers. Photos of the freeze lining following the first campaign are shown in Figure 7 and following the latest campaign in Figure 8. In some areas the freeze lining dislodged naturally from the hot face of the copper stars after cool down as shown in Figure 7 (a). In some areas the freeze lining was removed to measure its thickness. The thickness of the freeze lining on the hot face of the copper stars for the Row 2 coolers averaged between 5 and 10 mm. Approximately 2/3rds of the sacrificial refractory layer thickness was still present next to the copper stars. The remaining refractory found after removing the slag freeze layer is indicated by the orange arrow in Figure 7 (b). Figure 7 (c) shows a section where the slag freeze lining was removed to inspect the interface between adjacent Row 2 and 3 coolers. The slag freeze lining thickness averaged between 10 to 15 mm in this area.

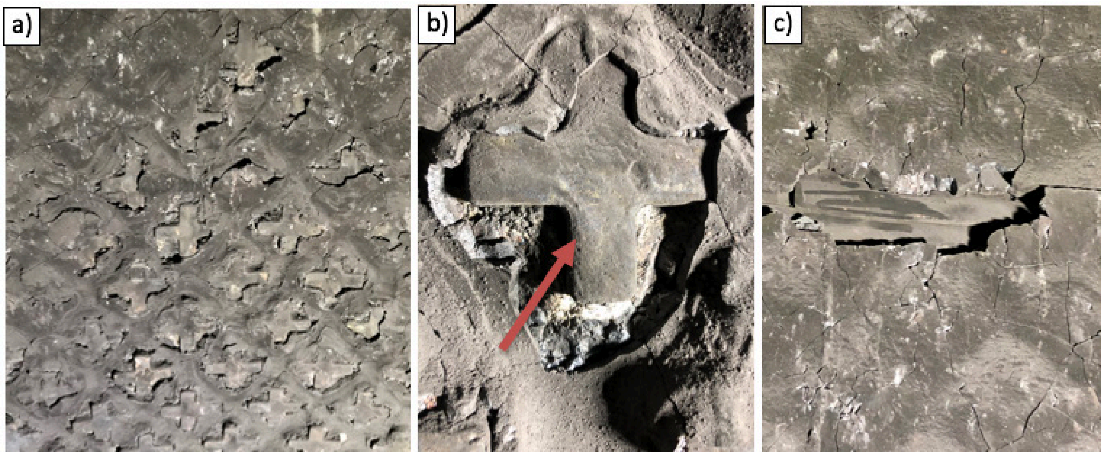

Figure 7: Freeze lining formation on MAXICOOL® cooler hot face following first operating campaign from 14 October to 12 December 2019.

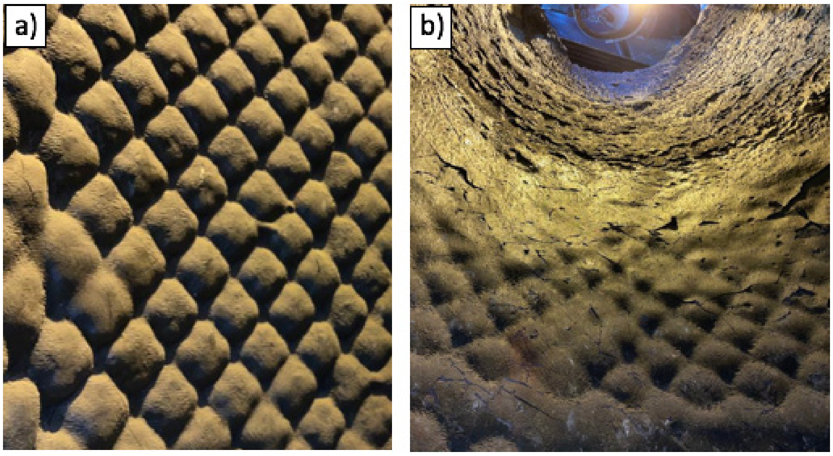

Figure 8: Freeze lining formation on MAXICOOL® cooler hot face following latest operating campaign during March to April 2021.

The slag freeze lining covering the Row 2 MAXICOOL® cooler hot face following the latest operating campaign is shown in Figure 8 (a). It indicates deeper valleys between the copper stars, which is assumed to indicate further wear of the sacrificial refractory layer since the first campaign. Further up the sidewall the valleys disappear and a smoother freeze lining surface is visible on the Row 3 cooler freeboard hot face as can be seen in Figure 8 (b). The average slag freeze lining thickness on the hot face of the copper stars has been estimated at 7 mm, again within the 5 to 10 mm range. To date no wear of the copper star hot faces has been noticed.

The operating data from the first 8 days during the latest campaign is graphically represented in Figure 9. The averages of the measured copper temperatures and calculated hot face heat fluxes for the Row 2 MAXICOOL® coolers are plotted against the measured slag and blister copper tapping temperatures. The dips visible in the calculated heat flux occurred during furnace stoppages to measure the bath depth amongst other reasons. During normal operation the calculated heat flux averaged between 60 to 80 kW/m^2, dipping to between 40 and 50 kW/m^2 for a short period on 29 March 2021, corresponding to lower slag and blister operating temperatures, and peaking at between 80 and 90 kW/m^2 during the initial and final periods. As expected, a general correlation between slag operating/tapping temperature and the cooler heat flux as well as copper temperatures is observed.

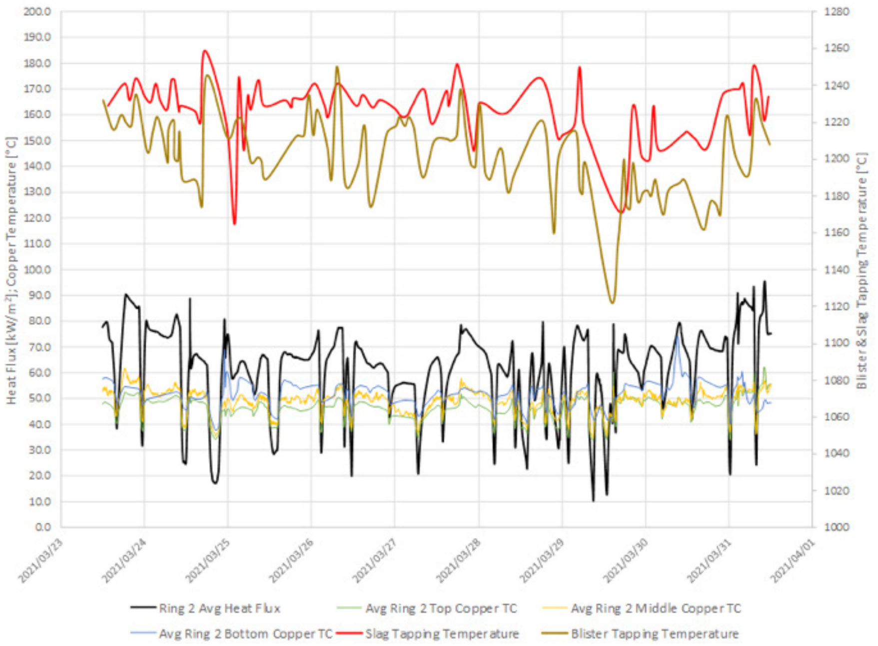

Figure 9: Average copper temperatures and calculated heat fluxes for the Row 2 coolers from the latest operating campaign during March to April 2021.

4.3 Performance evaluation

Whilst the average slag tapping temperature achieved is slightly below the operating temperature anticipated during the design phase under normal operating conditions (see Table 1), the resulting heat flux is higher than the 52 kW/m^2 anticipated during the design phase. The average measured copper temperatures are also higher, at 50 to 55°C, compared to the 40 to 43°C calculated during the design phase (Table 2). This is most likely due to the thicker freeze lining thickness of 30 mm considered during the design phase compared to the 5 to 10 mm measured in practice, which in turn relates to the slag freezing temperature and frozen slag thermal conductivity. In addition, the slag bath to freeze lining hot face heat transfer coefficient could be different to that anticipated.

To further evaluate these parameters and estimate their values that correlate to the measured data, additional thermal FEA modelling was conducted. In particular, calculating the value of the bath to sidewall heat transfer coefficient and the slag freeze lining thermal conductivity could help to better estimate these values for future design optimisation. For the purpose of the FEA modelling the following parameter values were assumed, based on the available operating data as well as the feedback from the operating personnel:

Slag bath temperature = 1230°C

Slag freezing temperature = 1200°C

Freeze lining thickness = 7.5 mm

Heat flux = 65 kW/m^2

The slag freezing temperature in particular was based on feedback from the operating personnel who indicated slag tapping became difficult at tapping temperatures below 1220°C, with solid inclusions being visible in the slag stream. In other words, the slag superheat is low and estimated at no more than 30°C from the phase equilibria defined for this system in Figure 6.

Considering above values and using Equation (1), the bath to sidewall heat transfer coefficient was calculated equal to 2167 W/m^{2}K, much higher than the 200 to 1000 range originally anticipated (see Table 1). This heat transfer coefficient was combined with the 1230°C slag bath temperature for the hot face boundary condition in the 3D FEA model. The model is shown in Figure 10. The model represents a symmetrical MAXICOOL® cooler section. A transient thermal analysis was performed with non-linear properties for the slag bath to calculate the freeze lining formation on the hot face. The results are presented in Figure 11.

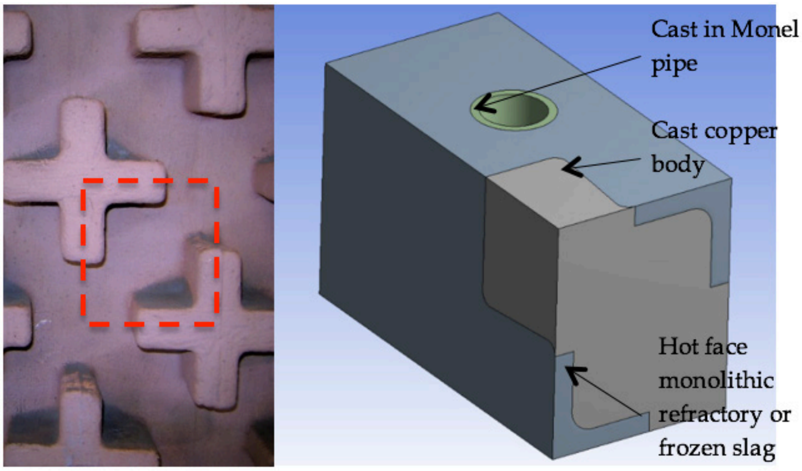

Figure 10: MAXICOOL® high intensity sidewall cooler model.

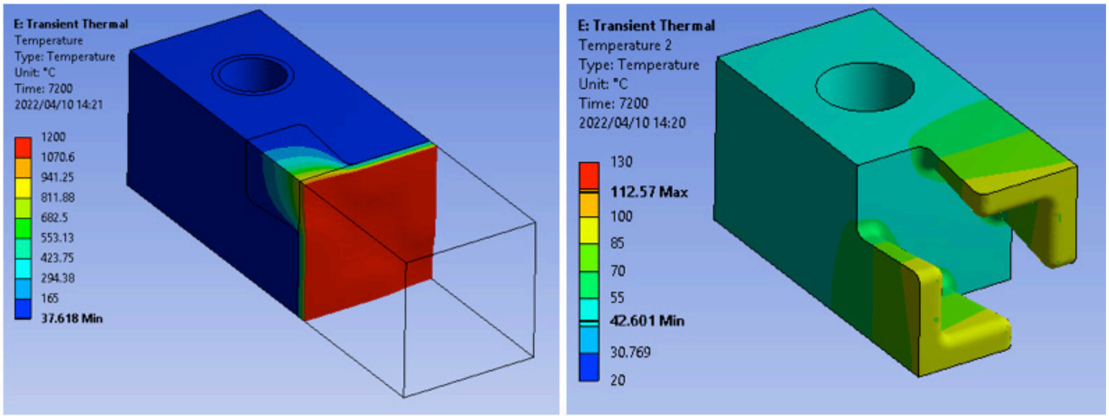

Figure 11: Thermal FEA modelling results.

The heat flux calculated in the FEA model is equal to 66.5 kW/m^2. By adjusting the freeze lining thermal conductivity to 0.7 W/mK, the freeze lining thickness stabilises at approximately 7 mm in front of the slag-retaining copper stars' hot face, and about 4 mm in front of the pockets between the copper stars. This compares well with the parameters assumed based on the operating data as well as the measured freeze lining thicknesses. The copper temperature at the same location, as measured in the actual cooler, is calculated by the FEA model to be approximately 50°C. This compares well with the 50 to 55°C copper temperatures measured during operation (Figure 9). The maximum copper temperature is calculated to be 113°C, which is well below the 400 °C design limit.

The good comparison between the calculated results from the FEA model and the operating data gives a high level of confidence that the bath to sidewall heat transfer coefficient is higher than originally estimated, and that the new value of 2167 W/m^{2}K is realistic. Furthermore, a freeze lining thermal conductivity of 0.7 W/mK results in a freeze lining thickness that correlates well with the actual freeze lining thickness measured on site.

5. Future improvements

Feedback from the operating personnel indicated that the furnace bath cools down quickly when the furnace is not operating. This is due to the large amount of heat being extracted by the sidewall copper cooling system whilst no additional heat is generated in the furnace bath. One option to reduce the heat loss during these non-operating periods is to reduce the cooling water flow rate. However, this is not easy to implement and control without risking localised boiling and damage to the copper coolers. A more realistic option proposed by the authors is to modify the hot face star design for future installations to reduce the rate of heat loss during the non-operating periods. By increasing the length of the stars the hot face thermal resistance between the bath and the cooling water will be increased. Whilst the heat loss during operation with a stable freeze lining is a function of the superheat and the bath to sidewall heat transfer coefficient and independent of the actual cooling system design (Joubert et al., 2019), the rate of heat loss once the operating conditions change until a new equilibrium is established, such as when the furnace is shut down, is a function of the cooling system design and its thermal resistance.

Such a design change must retain the ability to form and maintain a slag freeze lining during operation whilst maintaining the maximum copper temperature below the design limit of 400°C. To test this, a preliminary design change involving the doubling of the copper star length has been modelled using thermal FEA and the same boundary conditions used to evaluate the actual operating conditions. The FEA results are shown in Figure 12. The heat flux is 68.3 kW/m^2, close to that for the existing design as it is determined by Equation (1) once a stable freeze lining has formed. The freeze lining thickness is approximately 6 mm in front of the stars and 1 mm in front of the pockets. The maximum copper temperature is 181°C, higher than for the existing design but well below the 400°C design limit. Based on this analysis, such an updated design will be able to cope with the furnace operating conditions and maintain a stable freeze lining, whilst reducing the heat loss rate once the furnace is shut down. As noted, this is a preliminary design change to illustrate what is possible. This concept will be further developed for the next iteration of coolers and/or ISACONVERT™ installation.

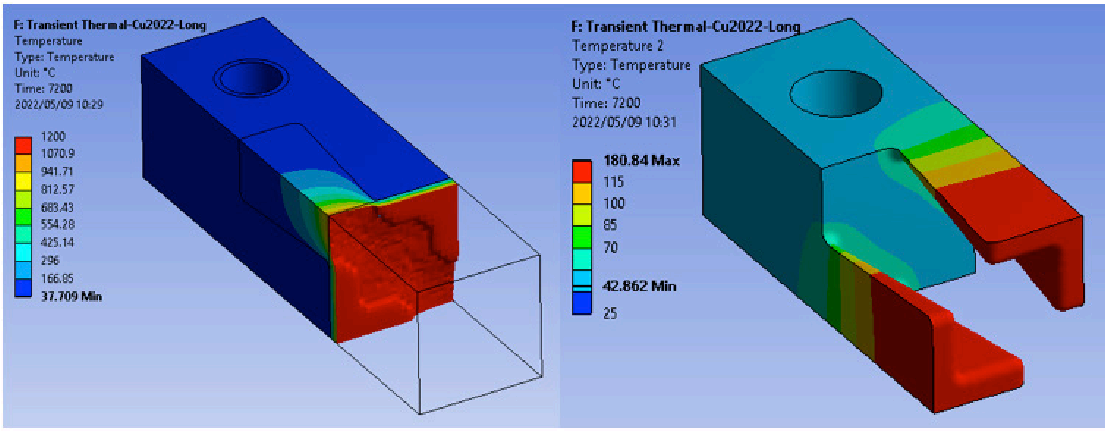

Figure 12: Thermal FEA modelling results for modified MAXICOOL® cooler.

6. Conclusions

The first commercial scale ISACONVERT™ furnace has successfully completed its first four operating campaigns at the Kansanshi Copper Smelter in Zambia. The treated matte rate steadily increased from 35 to 245 tonnes per day.

Tenova's high intensity MAXICOOL® copper sidewall coolers were installed to contain the slag bath. The coolers formed and maintained a stable slag freeze lining on their hot faces during all four operating campaigns. No refractory repairs or modifications to the sidewall coolers were required during the four campaigns.

An average heat flux between 60 and 80 kW/m^2 was measured during operation for the sidewall MAXICOOL® coolers. Considering the measured slag operating temperature and the observed slag freezing temperature, the slag bath to sidewall heat transfer coefficient was calculated to be 2167 W/m^{2}K. A slag freeze lining between 5 and 10 mm thick was observed on the hot face of the coolers adjacent to the slag bath.

Using the values measured during operation as boundary conditions in a non-linear thermal 3D FEA model of a MAXICOOL® cooler section, and adjusting the freeze lining conductivity to 0.7 W/mK, heat flux, freeze lining thickness and copper temperatures corresponding to those measured during operation were calculated. The good correlation between operating and calculated results provides for a high level of confidence in the FEA model and its future use to optimise the cooler design. The 3D FEA model was used to evaluate a potential modification to the cooler design to reduce the heat loss rate during non-operating periods.

References

De Vries D., Hunt S., Hanschar, L. (2016) Kansanshi Copper Smelter, Design, Commissioning and Operation, Copper 2016, Osaka, Japan, p616-629.

Edwards, J. S., GRF Alvear F. (2007). Converting Using ISASMELT™ Technology, Proceedings of the Sixth International Copper-Cobre Conference, Volume III, The Carlos Diaz Symposium on Pyrometallurgy, Book 2, pp 17-28.

Edwards, J.S. and Jahanshahi, S. (1999) "Copper Converting", United States Patent, No. 5,888,270, 30 March.

Eggert M., Dyussekenov N., Chirwa W., Hogg B., (2022) Preparing the ISACONVERT™ for commercial production at the Kansanshi Copper Smelter, in Copper 2022, Copper International Conference, Santiago, Chile, 2022.

Hunt S., De Vries D (2019) Kansanshi Copper Smelter: The first four years of operation, in COM2019, 58th Annual Conference of Metallurgists, Hosting the 10th International Copper Conference 2019.

Joubert, H., Nourse, R. B., Masters, B., & Hundermark, R. (2005). Copper cooling design, installation and operational results for the slag cleaning furnace at Waterval Smelter, Rustenburg Platinum, South Africa. In COM2005. 44th Conference of Metallurgists, International Symposium on Nickel and Cobalt Production.

Joubert H, Nikolic S, Bakker MI, Mc Dougall I, (2016) Tenova Pyromet – Cooled Copper Furnace Elements, Copper 2016, Osaka, Japan, p955-965

Joubert, H., & Mc Dougall, I. (2019). Designing furnace lining/cooling systems to operate with a competent freeze lining. In TMS 2019 148th Annual Meeting & Exhibition Supplemental Proceedings (pp. 1181-1195). Springer, Cham.

Joubert H., Mc Dougall I., De Villiers G. (2019) Design of copper cooling systems for copper smelting and converting furnaces, COM2019, 58th Annual Conference of Metallurgists, Hosting the 10th International Copper Conference 2019.

Mwanza, T., Eggert, M., Chirwa, W., Prince, M., Dyussekenov, N., Marschall, D. (2022). Kansanshi Copper Smelter ISACONVERT™ Furnace Tapping System Design, Operation, and Improvements. In: Steenkamp, J.D., Gregurek, D., Reynolds, Q.G., Alvear Flores, G., Joubert, H., Mackey, P.J. (eds) Furnace Tapping 2022. The Minerals, Metals & Materials Series. Springer, Cham. https://doi.org/10.1007/978-3-030-92544-4_17

Mc Dougall, I (2014), Tenova Pyromet External Communication, XT2-IM-TC Temperature 20140227 Rev 4.

Nikolic S., Hayes P. C. and Jak E., (2008) “Phase Equilibria in Ferrous Calcium Silicate Slags Part III: Copper saturated slag at 1250oC and 1300oC at an oxygen partial pressure of 10-6atm”, Metal. Mater. Trans. B, 2008, vol 39(2), pp.200-209

Nikolic S., Hayes P. C. and Jak E. (2009) “Experimental Techniques for Investigating Calcium Ferrite Slags at Metallic Copper Saturation and Application to Systems “Cu2O”-“Fe2O3” and “Cu2O”-CaO at Metallic Copper Saturation”, Metal. Mater. Trans. B, 2009, vol 40(6), pp.892-899.

Nikolic S., Hayes P. C. and Jak E., (2008) “Liquidus Temperatures in the “Cu2O”-FeO-Fe2O3-CaO System at Metallic Copper Saturation”, Metal. Mater. Trans. B, 2008, vol 40(6), pp.900-909.