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DESIGN OF COPPER COOLING SYSTEMS FOR COPPER SMELTING AND CONVERTING FURNACES

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ABSTRACT

The use of sidewall copper cooling systems to prolong furnace campaign life is becoming an accepted technology solution in the base metals industry. Tenova Pyromet has designed and installed a number of sidewall copper cooling systems in base metals furnaces, including the platinum industry. Apart from increasing the furnace campaign life through the formation of a stable freeze lining, a well-designed copper cooling system enables the plant operator to focus more on optimizing the process to achieve throughput and recovery targets, and to accommodate more varied and available concentrate feed blends. The paper discusses the design of sidewall copper cooling systems for copper smelting and converting furnaces to achieve the above objectives. More specifically, the design of copper cooling systems for top submerged lance furnaces are discussed. An overall increase in furnace heat losses has been raised as a concern for intensively cooled sidewalls. The paper explores the overall heat loss expectations for copper cooled furnaces versus traditional refractory lined furnaces. In addition, the potential use of alternative cooling media is discussed.

KEYWORDS

Converting, Copper cooling, Freeze lining, Heat loss, Heat transfer, MAXICOOL®, Smelting, Top submerged lance

INTRODUCTION

Base metal smelting and converting furnace technologies have been evolving continuously over the past century to satisfy the need for higher throughput, improved efficiency, and longer campaign life. To accommodate these demands, in particular higher smelting intensity and throughput, furnace bath containment systems had to improve. The use of pure refractory lining systems has slowly made room for the use of more intensively cooled lining systems (Joubert, Nikolic, Bakker & Mc Dougall, 2016). These cooling systems evolved from external shell cooling, such as shower or film cooling, to copper plate coolers extending into the furnace refractory lining, and high intensity stave or panel coolers (Verscheure, Kyllo, Filzwieser, Blanpain & Wollants, 2006). Consequently, an increasing number of base metal smelting and converting furnaces are equipped with copper cooling systems, including flash furnaces (Bryk, Ryselin, Honkasalo, & Malmstrom, 1958; Yasuda, Motomura & Kawasaki, 2014; Marx, Shapiro & Henning, 2010), top submerged lance primary smelting and fuming furnaces (Bhappu, Larson & Tunis, 1994; Kim, Lee & Lee, 2000; MacRae & Steinborn, 2018), top submerged lance converting furnaces (Viviers & Hines, 2005; Nikolic, Hogg & Voigt, 2018), primary platinum smelting electric furnaces (Nelson, Stober, Ndlovu, De Villiers & Wanblad, 2005; Jones, 2005; Hundermark, De Villiers & Ndlovu, 2006; Mc Dougall, 2013), and electric slag cleaning furnaces (Joubert, Nourse, Masters & Hundermark, 2005).

The main purpose of a well-designed copper cooling system is to lower the furnace lining/cooling system temperature sufficiently to prevent or slow ongoing wear. If the copper coolers are integrated with a refractory lining the intent is either to lower the refractory lining temperature sufficiently to prevent further wear, or to form and maintain a slag freeze lining on the refractory lining hot face to protect it against further wear. All refractory wear mechanisms, whether chemical, mechanical or thermal, are temperature dependent (Joubert, 1997). If the lining/cooling system consists of copper coolers only, as is the case for Tenova Pyromet's high intensity MAXICOOL® copper cooler panels, the intent is to form and maintain a competent slag freeze lining on the hot face and prevent wear from taking place, under both normal and extreme operating conditions (Joubert & Mc Dougall, 2019). A well-designed lining/cooling system should enable the furnace operator to focus more on optimising the process chemistry to achieve higher throughputs, efficiency and recoveries, and less on protecting the lining.

This paper explores the benefits of a well-designed lining/cooling system for base metal furnaces. In particular, the design of a copper cooling system for a typical top submerged lance (TSL) primary copper smelting furnace is discussed. A comparison between an intensively cooled and a traditional refractory lined bath sidewall is made with regard to wear stabilisation, freeze lining formation and heat losses. In addition, the use of alternative cooling mediums for the copper cooling system is explored.

METHODS

To evaluate the lining/cooling system design of a TSL furnace, a typical large primary copper smelting furnace with a concentrate smelting capacity of up to 1.2 Mtpa and an internal shell diameter of 5.5 m is considered. Manual calculations as well as finite element analysis (FEA) modelling are used to evaluate lining temperatures, freeze lining formation and heat losses. In particular, the lining/cooling system design for the sidewall adjacent to the furnace bath is evaluated, whilst the heat losses are evaluated for the complete furnace. For all furnace zones, three general heat load and lining scenarios are considered:
- Scenario 1: New lining and normal operating conditions
- Scenario 2: Worn lining and normal operating conditions
- Scenario 3: Worn lining and extreme operating conditions

The applicable operating and boundary conditions for each scenario vary per furnace zone.

SLAG BATH ZONE

The slag bath height varies considerably for a batch tapping TSL furnace. For the purpose of this evaluation the slag bath sidewall zone is assumed to extend 2 m above the matte-slag tidal zone.

Operating and boundary conditions

The operating and boundary conditions used to evaluate the furnace sidewall lining/cooling system design adjacent to the slag bath are listed in Table 1. Heat transfer to the sidewall is limited to convection between the slag bath and the sidewall. The relatively high convection coefficients are due to the turbulent bath conditions present in TSL furnaces. The slag freezing temperature is chosen to be close to the liquidus temperature for primary copper smelting slags (Verscheure et al., 2006). More often the freezing temperature is assumed to be below the liquidus temperature, in which case it will be more difficult to form a freeze lining (Camforts, Blanpain & Wollants, 2009; Scholey, Richards & Samaraseka, 1991).

Table 1. Slag bath zone operating & boundary conditions

Description	Units	Condition Value	
		Normal	Extreme
Bath temperature	°C	1,185	1,250
Bath-to-sidewall heat transfer coefficient	W/m²K	600	1000
Cooling medium temperature	°C	35	35
Slag freezing temperature	°C	1,150	1,150
Freeze lining conductivity	W/mK	1.2	1.2

Typical refractory lined sidewall

For the refractory lined sidewall adjacent to the slag bath, a new working lining thickness of 500 mm is assumed (Scenario 1). A magnesia-chrome refractory material with a thermal conductivity of 2 W/mK is considered. For the worn lining scenarios (Scenario 2 &3) a remaining working lining thickness of 150 mm is assumed. A thickness of 150 mm has been selected as this is considered to be the minimum stable lining thickness. Below this thickness either the working lining itself or the remaining lining above is likely to become structurally unstable. The 76 mm thick backing lining is assumed to have thermal conductivity of 1.2 W/mK. The calculated temperature profiles through the sidewall lining for Scenarios 1 and 2 are shown in Figure 1.
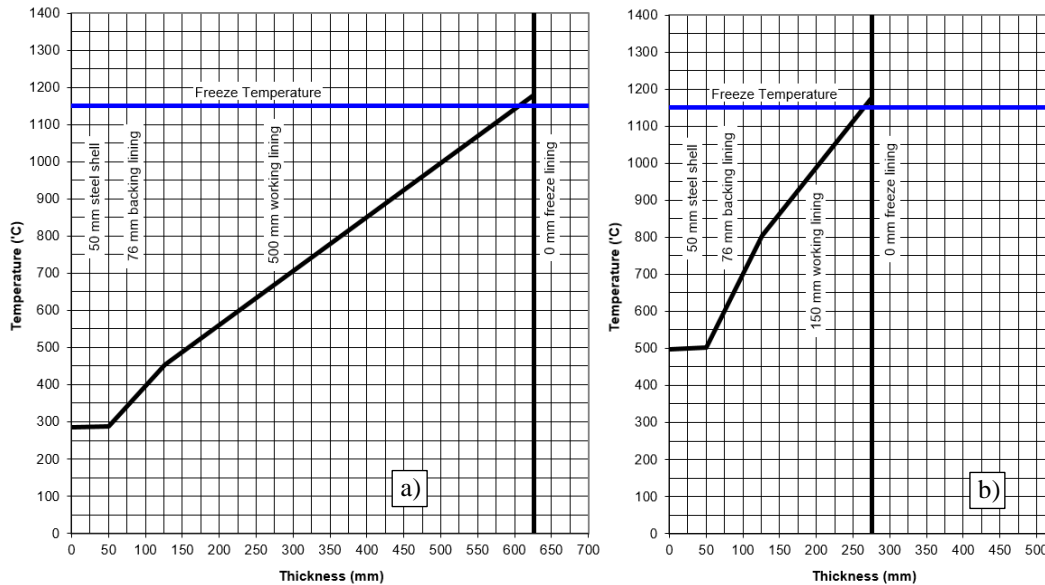

Figure 1. Calculated lining temperature profile under a) Scenario 1 and b) Scenario 2 adjacent to the slag bath and refractory lining only

The first observation is that a freeze lining is unlikely to form on the lining hot face for either Scenario 1 – New lining & normal operating conditions (Figure 1 a)) or Scenario 2 – Worn lining & normal operating conditions (Figure 1 b)). The same is true for Scenario 3 – Worn lining & extreme operating conditions (not shown). The calculated lining hot face temperatures are 1,180°C, 1,176°C and 1,245°C, respectively for Scenarios 1, 2 and 3. Further calculations show that even if the working lining is worn away completely, the backing lining hot face temperature under normal operating conditions is still above the freezing temperature at 1,173°C.

The second observation is the high shell temperatures predicted. For Scenario 1 a shell temperature of 286°C is calculated, and for Scenario 2 497°C. Actual shell temperatures may be lower due to contact resistances between the working and backing lining and the backing lining and the furnace shell. However, primary copper smelting TSL furnace shell temperatures are known to be very high, and the authors have witnessed temperatures in excess of 300°C. Many TSL furnace installations make use of either forced air or water cooling on the furnace shell to limit temperatures.

<u>Shell cooling</u>

Figure 2 shows the lining temperature profiles for Scenario 1 and 2 when forced water cooling is applied on the furnace shell. The furnace external shell temperatures are significantly reduced to 36°C and 38°C for Scenario 1 and 2, respectively. However, the lining hot face temperatures remain above the freezing temperature for both scenarios at 1,178°C and 1,171°C, respectively. The external shell cooling therefore

has a significant and positive effect on reducing shell temperatures, whilst having little to no impact on the lining hot face temperature. This is due to the relatively lower thermal conductivity of the refractory material dominating the overall lining thermal resistance (Joubert et al., 2019).
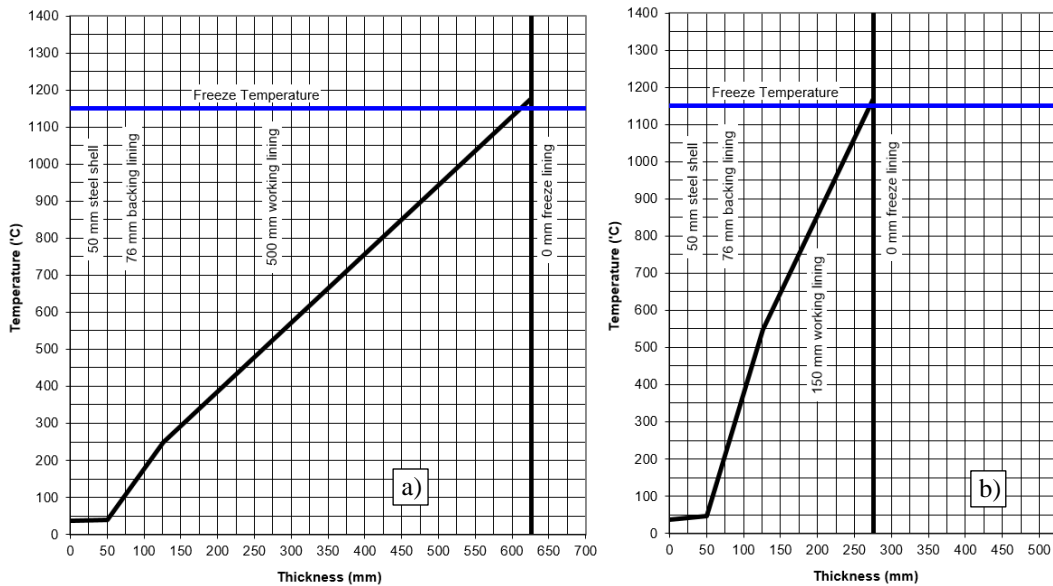

Figure 2. Calculated lining temperature profile under a) Scenario 1 and b) Scenario 2 adjacent to the slag bath and refractory lining only with external shell water cooling

Intensively cooled sidewall

For the intensively cooled sidewall lining adjacent to the slag bath, a water cooled copper panel such as Tenova Pyromet's MAXICOOL® copper coolers is considered (see Figure 3). A panel consists of high purity and conductivity cast copper with cast-in monel piping forming the cooling water circuits. A unique dovetail star pattern on the hot face of the coolers provides support for an initial castable refractory layer, and later for the slag freeze lining.

Figure 3. Example of Tenova Pyromet's MAXICOOL® sidewall coolers

The typical cooler thickness is approximately 200 mm with a steel backing support frame approximately 250 mm deep installed between the cooler and the shell to ensure that the hot face of the cooler lines up well with the refractory lining below in the bottom barrel zone adjacent to the matte-slag tidal zone. The typical arrangement of the MAXICOOL® copper cooler inside the furnace shell with the support frame is shown in Figure 4.
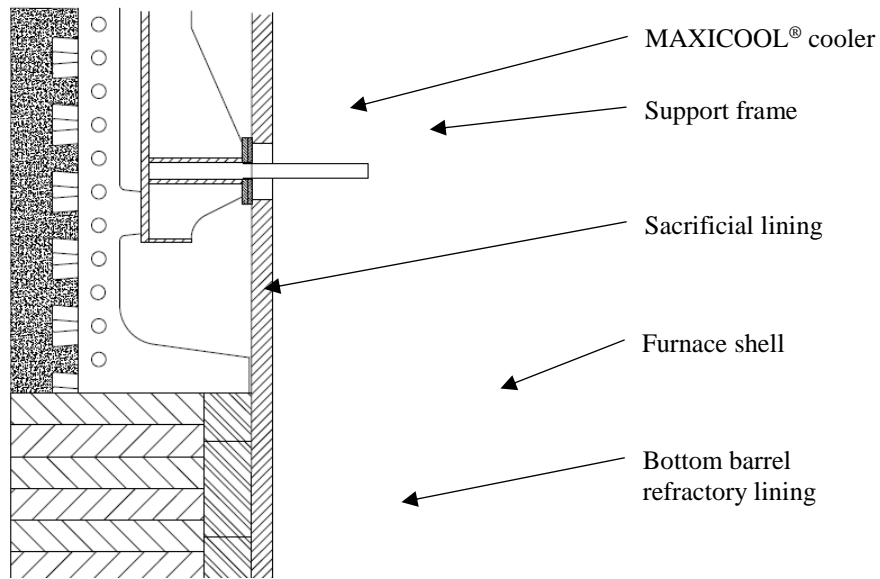
Figure 4. Typical arrangement of a MAXICOOL® cooler with support frame inside furnace shell

The calculated temperature profiles for the intensively cooled sidewall adjacent to the slag bath are shown in Figure 5. For Scenario 1 a 100 mm sacrificial castable refractory layer with a thermal conductivity of 3 W/mK is included on the hot face of the MAXICOOL® cooler (Figure 5 a)). The sacrificial layer is assumed to have worn away for Scenario 2 (Figure 5 b)). Castable refractory is assumed to remain between the slag retention 'stars' on the cooler hot face.

The main observation from Figure 5 is that a freeze lining will form on the cooler hot face under both Scenarios 1 and 2, with thicknesses of 23 and 62 mm, respectively. Importantly, calculations show that a freeze lining will also form for a worn lining exposed to extreme operating conditions, Scenario 3, with a thickness of 11 mm.
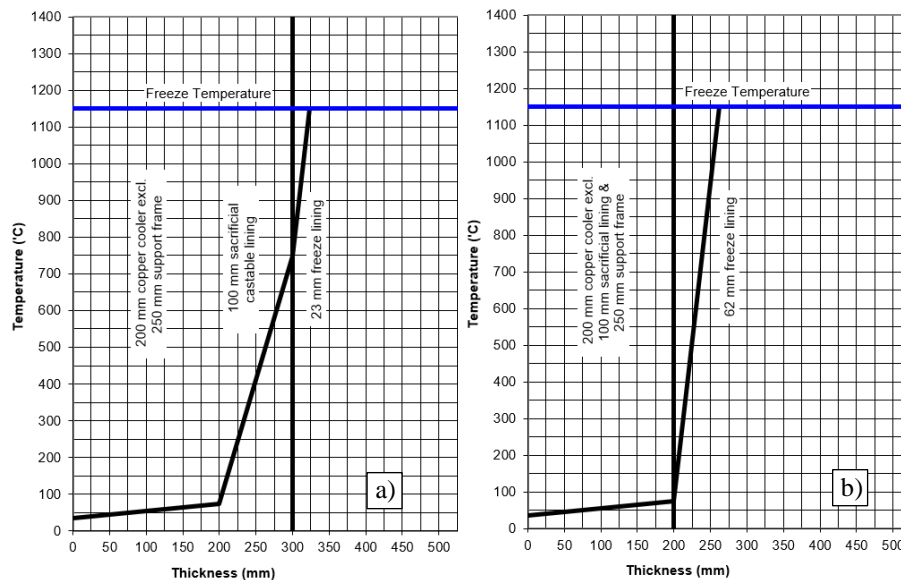

Figure 5. Calculated lining temperature profile under a) Scenario 1 and b) Scenario 2 adjacent to the slag bath and with MAXICOOL® copper cooling panels

<u>Benefits of intensive cooling</u>

Based on these results and observations, the following benefits can be realised for a furnace operator through the use of a well-designed intensive sidewall copper cooling system:

Increased lining life. Furnace operation is the most important factor influencing furnace lining life. A single abnormal event could be detrimental to the furnace lining. The campaign life of the lining, and consequently the furnace campaign life, is therefore not determined by the normal operating conditions, but by the extreme operating conditions. The aim is to form and maintain a slag freeze lining on the lining hot face, even under extreme operating conditions, to provide ongoing protection and increase the lining campaign life.

Increased production. A well-designed lining cooling system will allow higher smelting intensity resulting in higher furnace throughput. A higher smelting intensity may include higher operating bath temperatures and a less viscous slag. This has the further potential benefit of improving the ease of tapping of the furnace.

Improved process optimisation and flexibility. Intensive sidewall cooling offers the freedom to optimise the process chemistry, operating temperatures and slag viscosity among others whilst significantly reducing the constraint of refractory lining life considerations. In addition, it allows flexibility with regard to available concentrate streams and blends.

Reduced operating costs. A well designed intensively cooled copper lining, such as the MAXICOOL® system, will last longer than a pure refractory lining. Notwithstanding the higher capital expenditure for a copper cooling system, the reduced operating cost due to an increased furnace campaign life and furnace availability will ensure payback in the medium term.

HEAT LOSSES

Once a freeze layer has formed on the lining hot face, the heat losses are a function of process parameters such as slag superheat, viscosity and conductivity, and not of the cooling system design or cooling medium temperature. The heat flux through the furnace lining/cooling system will be governed by Equation 1 (Joubert et al., 2005):

$$q_{sidewall} = h_{bath}(T_{bath} - T_{freeze}) \qquad (1)$$

Where

$q_{sidewall}$ =   Heat flux through sidewall lining/cooling system in kW/m^2.

h_{bath} =   Heat transfer coefficient between the bath and the slag freeze layer in W/m^{2}K. This is mostly a function of the slag thermal conductivity, density and viscosity, as well as the induced bath turbulence and flow velocities in the case of a TSL furnace.

T_{bath} =   The operating bath temperature in K.

T_{freeze} =   The slag freezing temperature which is normally between the slag solidus and liquidus temperatures in K.

In contrast, the heat loss or flux through a refractory only sidewall lining, where no freeze lining is formed, will initially be very low and will increase as the refractory wears. The estimated heat losses for a large primary copper smelting TSL furnace are listed in Table 2. The listed heat losses are the sum for all furnace zones, including the hearth, bath sidewall, freeboard sidewall and boiler roof. Whilst the heat losses for the intensively cooled TSL furnace are higher than those for a typical refractory only lining design, the percentage increase in heat losses for a worn versus new lining is significantly less. Depending on the concentrate streams and blends available for smelting, higher heat losses for primary copper smelting TSL furnaces are not always a problem, and in some cases may be desirable (De Vries, Hunt, Dyussekenov, Milovanov & Chikashi, 2016). Due to the excess heat available in the furnace, the higher heat losses due to

the intensive copper cooling do not necessarily lead to an increase in operating costs, and the longer campaign life of the lining and the improved safety and ergonomic aspects of a lower shell temperature offset any perceived disadvantages of the higher heat loss.

Table 2. Heat losses for different copper TSL furnace lining/cooling system configurations

Lining/cooling system design	Units	Condition	
		Scenario 1 Normal - New lining	Scenario 2 Normal - Worn lining
Refractory only lining (typical copper TSL)	MW	1.8	2.7
Refractory lining with external shell cooling	MW	2.0	3.3
Extensively cooled lining/cooling system	MW	4.8	5.8

COOLER DESIGN & ALTERNATIVE COOLING MEDIA

Whereas the normal operating conditions determine the long-term heat losses from the furnace, the furnace campaign life is more a function of the extreme operating conditions (Joubert, 1997). It follows that a design objective for the sidewall lining/cooling system, and the copper cooling elements in particular, should be firstly to extract sufficient heat to establish, re-establish and maintain a freeze lining under all operating conditions, including extreme operating conditions. Secondly, the design of the lining/cooling system needs to ensure the integrity of the furnace and furnace sidewall under extreme operating conditions that may include the temporary loss of the freeze lining. A key aspect of sidewall integrity is the integrity of the copper cooling elements. Tenova Pyromet design sidewall copper cooling elements, such as the MAXICOOL® high intensity copper cooling elements, to operate at maximum copper temperatures below 400°C when subjected to extreme operating conditions. This is to ensure that the structural integrity of the copper cooling elements is maintained.

FEA models are employed to evaluate and optimise the design of copper cooling elements. The FEA model typically comprises the smallest symmetrical section of the proposed lining/cooling system, for example a symmetrical section of a MAXICOOL® copper cooling element as shown Figure 6. The refractory material in front of the copper cooling element is assumed to have worn back to the copper hot face pattern. Monolithic refractory material is retained between the stars forming the copper hot face pattern. As part of the extreme operating conditions, the slag freeze layer, which is likely to have formed, is assumed to have dislodged from the cooling element hot face, and the slag bath is assumed to be "washing" directly onto the cooling element hot face. A steady state thermal FEA is performed to represent the worst case, i.e. where no slag freeze lining reforms on the hot face. This worst-case assumption is significant considering that transient calculations show that a freeze lining will start forming immediately and that, as a result, the lining/cooling system hot face temperature will drop significantly within the first 5 to 10 minutes irrespective of the value of the process parameters (Joubert and Mc Dougall, 2019).
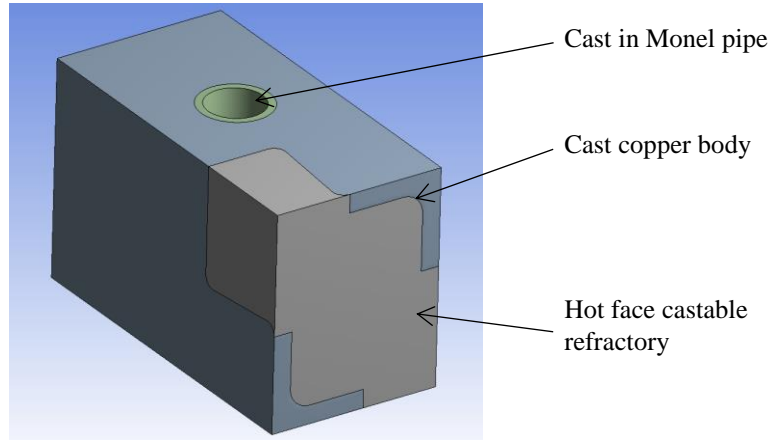
Figure 6. Symmetrical FEA model of MAXICOOL® copper cooling element

For this evaluation, a maximum bath temperature of 1,300°C is used, slightly higher compared to the extreme condition specified in Table 1, with a maximum bath to sidewall heat transfer coefficient equal to 1,000 W/m²K selected as boundary conditions to the hot face of the symmetrical MAXICOOL® copper cooling element thermal FEA model.

Three different cooling media are evaluated, all at a velocity of 2 m/s through the cast-in monel tubing. Monoethylene glycol (MEG) and ionic liquid are evaluated as potential safer alternatives to water (Kennedy, Nos and Weaver, 2013). For water a bulk temperature of 35°C and a cooling heat transfer coefficient calculated as 9,340 W/m²K are used. For MEG and ionic liquid, a temperature of 60°C and heat transfer coefficients of 1,730 W/m²K and 600 W/m²K, respectively, are calculated using available material properties (Kennedy et al., 2015).

The thermal FEA modelling temperature results, isolated for the copper only, are presented in Figure 7. The maximum copper temperature for water cooling under these extreme operating conditions is calculated to be 333°C as shown in Figure 7 (a). This is well below the maximum design limit of 400°C, even under these extreme operating conditions. For both MEG Figure 7 (b)) and ionic liquid Figure 7 (c)) the maximum copper temperatures are above the 400°C design limit, calculated to be 446°C and 607°C, respectively.

An option is to increase the flow rate and velocity of the MEG and ionic liquid to improve the respective heat transfer coefficients and to limit the cooler copper temperature. The results for increasing the average linear velocity to 4 m/s are shown in Figure 8. For MEG the maximum copper temperature is limited to 392°C, below the design limit, whilst for ionic liquid the maximum copper temperature remains well above the design limit at 493°C. For ionic liquid even higher average velocities may need to be considered for the stated extreme operating conditions. For both MEG and ionic liquid the implications of higher velocities combined with higher viscosities on pumping requirements and costs need to be further explored.
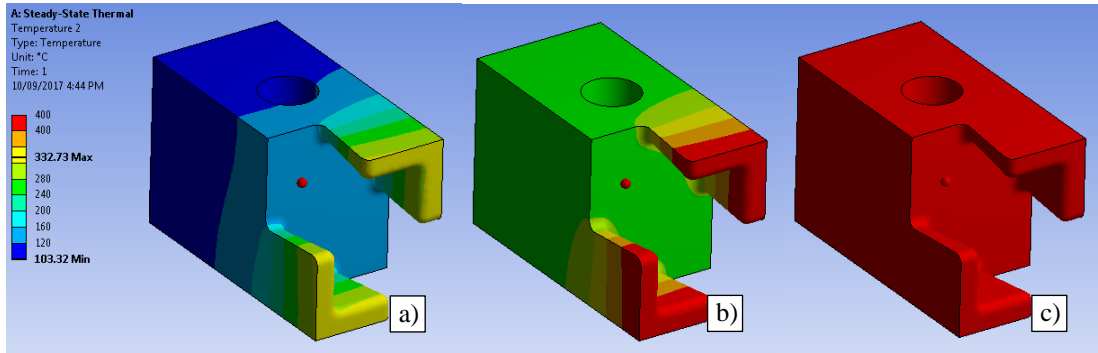
Figure 7. Steady state thermal FEA copper temperature plot results for a symmetrical section of a MAXICOOL® copper cooling element employing a) water, b) MEG and c) ionic liquid as the cooling medium
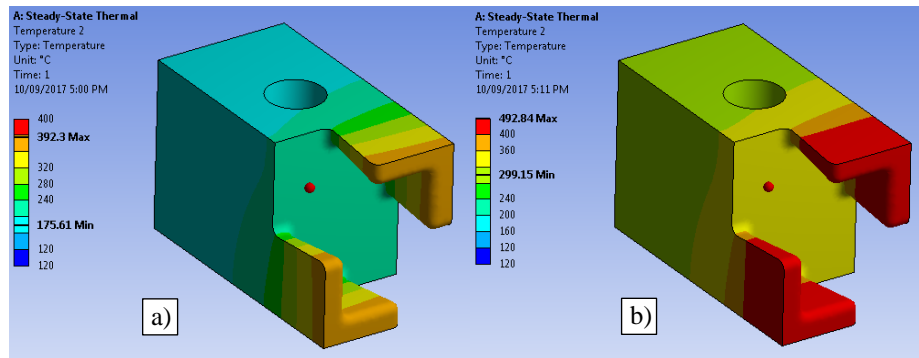

Figure 8. Steady state thermal FEA copper temperature plot results for a symmetrical section of a MAXICOOL® copper cooling element employing a) MEG and b) ionic liquid as the cooling medium at 4 m/s

CONCLUSIONS

This paper explores the benefits of a well-designed lining/cooling system for base metal furnaces, with particular reference to the design of a copper cooling system for a typical top submerged lance (TSL) primary copper smelting furnace.

Comparing the ease of formation of a freeze lining and the heat losses between an intensively cooled and a traditional refractory lined bath sidewall, it is demonstrated that a freeze lining is unlikely to form on the lining hot face for a new or worn lining (even if the lining is worn away completely to the backing lining) of the traditional lining configuration, whether under normal operating conditions or extreme operating conditions. In addition, high shell temperatures are predicted and observed. The shell temperature may be significantly reduced by the addition of water or forced air cooling, but this has a negligible effect on the lining hot face temperature. By contrast, when the lining is replaced with intensively cooled copper panels, a freeze lining will form on the cooler hot face for both normal and extreme operating conditions.

The benefits which can be realised for a furnace operator through the use of a well-designed intensive sidewall copper cooling system include increased lining life, as the copper cooler panels are not as sensitive to upset conditions as a traditional lining, due to rapid reforming of the freeze lining. This leads to increased production, as campaigns may be longer and the increased smelting intensity which may be achieved can result in higher furnace throughput. The robust lining provides the freedom to optimise the process chemistry, operating temperatures and slag viscosity among others, whilst significantly reducing the

constraint of refractory lining life considerations. Reduced operating costs can be achieved due to the longer campaign life, greater throughput and greater furnace availability.

The heat loss or flux through a refractory only sidewall lining, where no freeze lining is formed, will initially be very low and will increase as the refractory wears. Whilst the heat losses for the intensively cooled TSL furnace are higher than those for a typical refractory only lining design, the percentage increase in heat losses for a worn versus new lining is significantly less.

Tenova Pyromet design their sidewall copper cooling elements, such as the MAXICOOL® high intensity copper cooling elements, to operate at maximum copper temperatures below 400°C when subjected to extreme operating conditions. This is to ensure that the structural integrity of the copper cooling elements is maintained. MEG and ionic liquid were evaluated as potential safer alternatives to water. The thermal FEA modelling temperature results indicate that the maximum copper temperature for water cooling under extreme operating conditions is well below the maximum design limit. For both MEG and ionic liquid, the maximum copper temperatures are above the 400°C design limit for the extreme operating conditions considered and the same bulk velocities. Further work is required to confirm the perceived safety advantages and quantify the cost implications of using MEG or ionic liquid as alternative cooling media.

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