Designing Furnace Lining/Cooling Systems to Operate with a Competent Freeze Lining

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Abstract The formation of a freeze lining on the hot face of furnace sidewalls to increase campaign life is an accepted concept in industry today. This is achieved through a well-engineered sidewall cooling system typically consisting of cooled copper elements, either on their own or in combination with a refractory lining. The design of the lining/cooling system to form and maintain a competent freeze lining is discussed. Heat losses under normal operating conditions are calculated as an input to the furnace energy balance. The lining/cooling system is evaluated under extreme operating conditions as this ultimately determines campaign life. Variables to be evaluated include freeze lining thickness and formation rate, copper element temperatures, cooling medium used, and required cooling density and arrangement. Steady-state and transient thermal FEA are used as tools to evaluate the lining/cooling system design.

Keywords Freeze lining · Furnace cooling · Furnace integrity · Copper cooling · Heat transfer

Introduction

"Irrespective of the use of so called refractory materials, the best means of maintaining the walls of the blast furnace is with cooling water." These words were spoken in 1892 by Burteaux et al. [1], a well-known iron blast furnace operator from the late nineteenth century. Over the past century, the design of lining/cooling systems to prolong furnace campaign life has developed significantly, first in the steel industry and later in the base metals industry. Today an increasing number of furnaces used

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for base metal slag cleaning [2], primary platinum smelting [3–7], base metal flash smelting [8–10], top submerged lance primary smelting and fuming [11–13], and top submerged lance converting [14, 15] are designed and equipped with sidewall copper cooling elements. The copper cooling elements operate either on their own or in combination with a refractory lining. In all cases, the intent is for the copper cooling elements to reduce the lining/cooling hot face temperature sufficiently to prevent or reduce the wear of the furnace sidewall [16].

In the case where refractory material is used in combination with the copper cooling elements, the intent is to reduce the refractory hot face temperature sufficiently to either limit the rate of thermal, chemical and/or mechanical attack, or to freeze a layer of material (typically slag) on the refractory hot face and prevent or limit further wear due to the direct contact between the refractory material and molten bath [7, 17]. The frozen layer of slag is generally called a 'freeze lining'. In the case where copper cooling elements are used on their own or with a limited sacrificial refractory layer for furnace start-up, the intent is to establish and maintain a freeze lining that will prevent wear of the sidewall and limit heat losses [2, 18]. Theoretically, the freeze lining, if maintained, should extend the furnace sidewall campaign life indefinitely, or at least for an extended period [16]. Whilst the freeze lining will protect well-designed copper cooling elements against thermal and mechanical wear mechanisms, there are examples of chemical wear of the copper cooling elements taking place even behind the freeze lining. In particular, sulphidation corrosion of copper cooling elements has been observed and well documented in the platinum industry [19, 20].

The paper focuses on the design of the furnace sidewall lining/cooling system to establish and maintain a protective freeze lining on its hot face. The scope is limited to heat transfer modelling and consideration of some macroscopic process parameters. The sensitivity of the freeze lining thickness and formation rate to various parameters and properties including assumed slag freezing temperature, bath to sidewall heat transfer coefficient, thermal conductivity, freeze lining to lining/cooling system hot face contact resistance, and the cooling system design are explored. Finally, the paper explores the importance of these parameters when designing a sidewall lining/cooling system and in particular copper cooling elements.

Normal Operating Conditions and Heat Loss

For a typical continuously fed, batch tapped smelting furnace the operating conditions that impact the sidewall integrity can be described as normal when:

- Bath temperature is within the target range;
- Feed rate is stable;
- Feed composition is within specification;
- Slag chemistry is under control and well defined;
- Bath levels are measured, well controlled and within the targeted range;

- Energy input, whether by feed source, fuel or electrical, is stable and within targeted energy balance.

A well-designed sidewall lining/cooling system must ensure the formation of a stable freeze lining on its hot face under these normal operating conditions. The freeze lining thickness may vary slightly as the bath temperature and slag chemistry fluctuate within defined target ranges and as the bath-level changes due to batch tapping. Even so, as long as there is a fairly stable freeze lining in place, the heat load on the sidewall will be a function of the process parameters and not the sidewall lining/cooling system design. The heat load on the sidewall is the product of the bath to freeze lining heat transfer coefficient and the bath (normally slag) superheat as per Eq. (1). Linear (one dimensional) heat transfer is considered here for illustrative purposes.

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

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).

The slag freezing temperature refers to the bath-freeze lining interface temperature, and can alternatively be described as the freeze lining hot face temperature. It is common practice to set the slag freezing temperature equal to the bath (slag) liquidus temperature [21]. It has been reported in more recent work by others that the local slag freezing temperature at the bath-freeze lining interface can differ from the bath liquidus temperature due to the solidification rate and the microstructure of the freeze lining at the interface during formation, and that the slag freezing temperature at the interface varies between the so-called glass transition temperature and the bath liquidus temperature, with the glass transition temperature typically estimated as two-third of the liquidus temperature [22, 23]. From Eq. (1) it follows that the lower the selected slag freezing temperature relative to the bath temperature, the higher the heat load on the sidewall lining/cooling system will be, and the harder it will be to maintain a stable freeze lining. For design purposes, Tenova Pyromet uses a relatively conservative slag freezing temperature equal to the average of the liquidus and solidus slag temperatures as per Eq. (2) [18]. This is in part to approximate the effect of the so-called "mushy zone" or higher viscosity layer present close to the freeze lining hot face [24]. This value needs to be evaluated on a case by case basis and will depend on the actual slag composition. It may be more practical to select a slag freezing temperature closer to the slag liquidus temperature in some cases.

$$T_{freezing} = \frac{T_{liquidus} + T_{solidus}}{2} \tag{2}$$

Determination of the heat transfer coefficient between the bath and the freeze lining, h_{bath}, is important as it directly affects the sidewall heat load estimation. Methods for the estimation of this heat transfer coefficient include the use of physical experimentation, empirical relations and computational fluid dynamics (CFD) analysis. In most cases, a combination of these methods is employed. Kang [25] combined experimental and modelling work to develop an empirical relation for the heat transfer coefficient between an electric furnace slag bath and sidewall. The relation is based on natural convection heat transfer as shown in Eq. (3), from which the heat transfer coefficient can be calculated. Critical to the accuracy of this method is the estimation of slag properties, including density, viscosity, volumetric expansion coefficient, specific heat and thermal conductivity [26, 27]. A description for estimating the bath to sidewall heat transfer coefficient using this method was previously published by Joubert et al. [18]. The heat transfer coefficient has been found to range between 100 and 300 W/m^2K for molten bath submerged arc furnace applications.

$$Nu = C(Gr\,Pr)^m \tag{3}$$

for $8 \times 10^6 < Ra = Gr\,Pr < 10^{11}$
where

- Nu Nusselt number
- Gr Grashof number
- Pr Prandtl number
- Ra Rayleigh number
- C 0.32
- m 0.3.

For certain furnace applications such as top submerged lance furnaces, Pierce Smith converters and zinc fuming furnaces (box fumers) amongst others, the bath dynamics are such that forced convection takes place between the bath and the furnace sidewall. Estimation of the forced convection heat transfer coefficient between the bath and sidewall depends greatly on the actual bath velocities and velocity profiles adjacent to the sidewall. Scholey et al. [24] estimated the heat transfer coefficient between the bath and the steel cooling jacket for a zinc fuming furnace as 1100 W/m^2K. The estimation was based on using actual heat loss and bath temperature measurements during a furnace heating stage and following the dislodgment of the frozen slag layer (freeze lining) from the jacket hot face. The slag bath was in direct contact with the steel jacket hot face during this period. Using the Reynolds number analogy for turbulent flow over a flat plate and estimated slag velocity and properties, the heat transfer coefficient was found to be within the same range.

Steady-State Freeze Lining Thickness

Under steady-state conditions the heat loss through the furnace sidewall must be equal to the heat load or input from the furnace bath. Assuming linear heat transfer, the heat flux through the sidewall must be equal to the heat flux into the sidewall, as indicated in Eq. (4).

$$q_{out} = q_{in} = \frac{T_{bath} - T_{freezing}}{R_{bath}} = \frac{T_{bath} - T_{freezing}}{\frac{1}{h_{bath}}} \tag{4}$$

In turn, the heat flux through the sidewall is equal to the temperature gradient divided by the sum of the thermal resistances as per Eq. (5).

$$\begin{aligned} q_{out} &= \frac{T_{freezing} - T_{cooling}}{R_{freeze} + R_{lining/cooling}} \\ &= \frac{T_{freezing} - T_{cooling}}{\frac{x_{freeze}}{k_{freeze}} + \frac{1}{h_{fc}} + \frac{1}{h_{lcs}} + \frac{1}{h_c}} \end{aligned} \tag{5}$$

where

$T_{cooling}$ bulk temperature of cooling medium i.e. water (K or °C)
x_{freeze} freeze lining thickness (m)
k_{freeze} freeze lining thermal conductivity (W/mK)
h_{fc} heat transfer coefficient representing contact resistance between freeze lining and lining/cooling system hot face (W/m^2/K)
h_{lcs} effective lining/cooling system heat transfer coefficient (W/m^2/K)
h_c cooling medium heat transfer coefficient (W/m^2/K).

For a furnace sidewall incorporating copper cooling elements with or without refractory material, a three-dimensional thermal finite element analysis (FEA) model is used to calculate the effective lining/cooling system heat transfer coefficient [18]. For high intensity sidewall copper cooling elements such as Tenova Pyromet's MAXICOOL™ copper cooling elements (Fig. 1) incorporating a monolithic refractory on the hot face, the effective lining/cooling system heat transfer coefficient is approximately 100 W/m^{2}K [2, 29]. For copper plate coolers installed in a refractory brick lining, the effective heat transfer coefficient has been estimated to be 70 W/m^{2}K assuming the brick lining has uniformly worn back to the plate cooler hot face position and depending on the plate cooler installation density.

Combining Eqs. (4) and (5) and solving for the freeze lining thickness we obtain:

$$x_{freeze} = k_{freeze}\left[\frac{T_{freezing} - T_{cooling}}{T_{bath} - T_{freezing}}\left(\frac{1}{h_{bath}}\right) - \left(\frac{1}{h_{fc}} + \frac{1}{h_{lcs}} + \frac{1}{h_c}\right)\right] \tag{6}$$

Fig. 1 Tenova Pyromet's MAXICOOL™ copper cooling system [2, 29]

Equation (6) shows that the freeze lining thickness:

- Is directly proportional to the freeze lining thermal conductivity
- Increases as the bath superheat decreases due to a decreasing bath temperature
- Increases proportionally even more if the bath superheat decreases due to an increasing slag freezing temperature
- Increases as the bath to freeze lining/sidewall heat transfer coefficient decreases.
- Increases as the overall lining/cooling system thermal resistance decreases.

The sensitivity of the freeze lining thickness to changes in each of the variables will depend on the actual value and range of each variable. As an example, the typical values and range for each variable are assumed as listed in Table 1. Most of the values are typical for a molten bath submerged arc furnace such as a nickel slag cleaning furnace. The typical value of 300 W/m^2K for the heat transfer coefficient representing the contact resistance between the freeze lining and the lining/cooling system hot face, h_{fc}, has been proposed by Scholey et al. [24] for zinc fuming furnaces. It is only applicable once the frozen freeze lining has been established. A maximum value of 10,000 W/m^2K is included to represent the case where extremely good contact is maintained between the freeze lining and the lining/cooling system hot face. The range of cooling medium temperatures, $T_{cooling}$, and heat transfer coefficients, h_c, have been selected to cover various cooling mediums including water, Mono-Ethylene-Glycol (MEG), synthetic oil and ionic liquids [30, 31].

In Table 1 the freeze lining thickness is first calculated from Eq. (6) considering the typical values for all the variables. Second, the effect of the anticipated minimum and maximum values for each variable on the freeze lining thickness is calculated whilst maintaining the typical values for all the other variables. It is important to note that the estimated freeze lining thicknesses are an average across the lining/cooling system hot face and in practice the thickness may differ across the hot face in response to local differences in thermal conditions, and depending in particular on the copper cooling element design. For example, for an effective lining/cooling system heat

Table 1 Typical values and range for variables affecting freeze lining thickness as for a nickel slag cleaning furnace

Variable	Units	Typical value	Variable range		x_{freeze} Typical (mm)	x_{freeze} Range (mm)		x_{freeze} Sensitivity (%)
			Minimum	Maximum		Variable Min	Variable Max	
k_{freeze}	W/mK	0.75	0.5	1.5	24	16	47	50
T_{bath}	°C	1350	1300	1450		38	11	54
$T_{freezing}$	°C	1180	1100	1250		11	51	64
h_{bath}	W/m^2K	150	100	250		40	10	60
h_{fc}	W/m^2K	300	100	10,000		19	26	17
h_{lcs}	W/m^2K	100	70	100		20	24	7
h_c	W/m^2K	9,000	530	12,000		22	24	3
$T_{cooling}$	°C	35	25	80		24	22	4

transfer coefficient of 70 W/m^2K that is representative of a copper plate cooler design, there will likely be areas of the lining/cooling system hot face with no freeze lining present, and further wear of the refractory bricks in these areas are likely.

Percentage values listed in the last column of Table 1 indicate the relative sensitivity of the freeze lining thickness to the expected range of values for the various variables included in Eq. (6). The relative sensitivity is calculated as per Eq. (7).

$$Sensitivity_{x_{freeze}} = \frac{\frac{Absolute\left(x_{freeze\max} - x_{freeze\min}\right)}{2}}{\frac{x_{freeze\max} + x_{freeze\min}}{2}}\% \tag{7}$$

The process parameters and slag properties have the greatest influence on the freeze lining thickness. This includes the effect of varying freeze lining thermal conductivity, k_{freeze}, a changing slag superheat due to changes in either the bath temperature, T_{bath}, or the slag freezing temperature, $T_{freezing}$, and changes in the bath to sidewall heat transfer coefficient, h_{bath}. The values for these parameters are, in turn, affected by other process parameters such as feed composition, slag chemistry, energy balance, throughput as well as operating practices. The sidewall heat transfer coefficient can, in addition, be affected by the furnace design and dimensioning [28, 32–34]. As discussed previously, the slag freezing temperature, $T_{freezing}$, is influenced by the freeze lining microstructure. The freeze lining thermal conductivity, k_{freeze}, is affected by both the slag composition and the freeze lining microstructure [26, 27, 36, 37].

As noted Eq. (6) determines that the freeze lining thickness is directly proportional to values for k_{freeze}. In this evaluation, a maximum value for k_{freeze} of three times that of the minimum value results in a predicted maximum freeze lining thickness three times higher than the minimum thickness. The ratio between the maximum and minimum freeze lining thermal conductivities selected for this evaluation compare well with ratios that have been reported for other slag systems based on experimental results [36, 37], even though the absolute thermal conductivity values measured for these slag systems are substantially different and higher compared to the values used in this evaluation. The freeze lining thickness values will, however, increase with increasing freeze lining thermal conductivity even though the ratios will remain similar.

Whilst the selected values in Table 1 for both the bath temperature, T_{bath}, and the slag freezing temperature, $T_{freezing}$, affect the slag superheat equally, Eq. (6) indicates that the freeze lining thickness is more sensitive to the slag freezing temperature than the bath temperature. For example, a lower slag freezing temperature will increase the slag superheat, which will result in a thinner freeze lining, assuming that the bath temperature remains unchanged. In addition, the lower slag freezing temperature implies a smaller dT across the freeze lining and thus a thinner freeze lining. The lower dT across the freeze lining is incorporated in the $T_{freezing} - T_{cooling}$ term in Eq. (6).

As is the case for the heat loss from the furnace, once a freeze lining has been established and reasonably steady state conditions achieved, the effect of changing the lining/cooling system design parameters is insignificant in its effect on the freeze lining thickness in comparison to the effect of changing the process parameters. The importance of the lining/cooling system design as well as the selected cooling medium is to ensure that a stable and uniform freeze lining is established and the integrity of the sidewall and furnace as such are maintained. This becomes apparent when evaluating the lining/cooling system design under extreme operating conditions.

Transient Freeze Lining Formation

Furnace operating conditions do fluctuate in practice, and steady-state conditions can rarely be maintained over longer periods. The freeze lining thickness will fluctuate due to fluctuating operating conditions. Sometimes the freeze lining may dislodge completely from the lining/cooling system hot face in some areas for various reasons. Following such an event, the molten slag bath will wash up directly against the lining/cooling system hot face and the freeze lining will begin to reform. It is important to understand how the lining/cooling system will react and perform under these transient conditions. As steady state conditions do not exist anymore, Eq. (4) does not hold and the heat load/input on the sidewall is no longer equal to the heat output/through the sidewall. The new transient sidewall heat balance is described by Eq. (8). It includes the latent heat of formation or fusion term used to describe the heat removed to form the freeze lining or, when negative, the heat absorbed to melt the freeze lining over time.

$$q_{out} = q_{in} + \rho L \frac{dx_{freeze}}{dt} \tag{8}$$

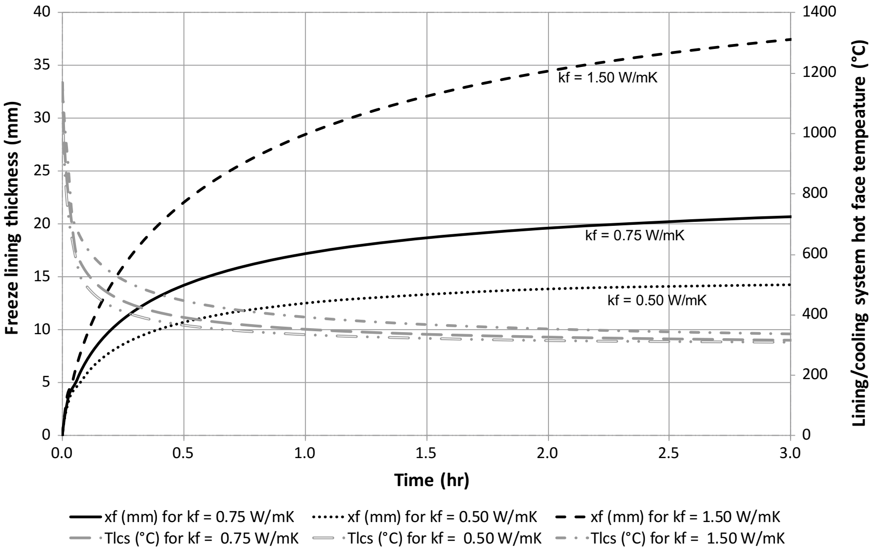

Fig. 2 x_{freeze} and T_{lcs} during freeze lining formation for different values of k_{freeze}

where

ρ bulk density of slag (kg/m^3)
L latent heat of fusion for slag (J/kg).

Using Eq. (8) the growth of the freeze lining can be calculated over time assuming a zero starting point and otherwise steady state conditions. These conditions are representative of what can be expected in a furnace following the dislodging of an existing freeze lining with the bath washing over the hot face of the lining/cooling system. In Fig. 2 the calculated change in freeze lining thickness, x_{freeze}, and the average lining/cooling system hot face temperature, T_{lcs}, are graphically represented relative to time passed. This is calculated for the same range for each variable listed in Table 1. As was the case for the steady state calculations, it was found that changes to the process parameters have a significantly greater effect on freeze lining formation compared to the lining/cooling system design parameters. Only the calculation results relative to changes for the four main process parameters, namely k_{freeze}, T_{bath}, $T_{freezing}$ and h_{bath}, are shown. In each case all other parameters are kept at the typical values listed in Table 1. The presented calculation results are limited to the first three hours of freeze lining formation.

For all calculations, the heat transfer coefficient representing the thermal contact resistance between the freeze lining and the lining/cooling system, h_{fc}, is initially kept very high and gradually decreased to the typical value of 300 W/m^{2}K once a freeze lining thickness of 5 mm has been achieved. This is to simulate initial good contact between the freeze lining and the lining/cooling system before reaching the thermal resistance expected under steady-state conditions. The calculated lining/cooling system hot face temperature represents an average temperature across the lining/cooling system hot face. The hot face temperature may locally vary substantially depending on the lining/cooling system design. This is due to the same reasons previously discussed for the potential variation from the calculated average in freeze lining thickness across the hot face.

Figure 2 confirms that the freeze lining thermal conductivity, k_{freeze}, significantly affects the freeze lining thickness as noted in Table 1 for steady state conditions. Figure 2 further shows that the freeze lining thickness approaches its equilibrium steady state value more quickly for lower freeze lining thermal conductivity values and more slowly for higher thermal conductivity values. In addition, for the selected values, the freeze lining thermal conductivity has a limited effect on the lining/cooling system hot face temperature. This is due to the thermal resistance of the freeze lining dominating that of a lining/cooling system consisting of intensive copper cooling as assumed here. It can be shown that even for the higher freeze lining thermal conductivities applicable to other slag systems [36, 37], the lining/cooling system hot face temperature will become only slightly more sensitive to the freeze lining thermal conductivity range and ratios.

Figures 3 and 4 indicate that the freeze lining thickness will approach equilibrium more quickly for a higher bath superheat. This is more a function of the lower equilibrium freeze lining thickness associated with a higher superheat as shown in Table 1. The same holds for Fig. 5, where the lower equilibrium freeze lining thickness is approached more quickly due to a higher bath to sidewall heat transfer coefficient. A thinner freeze lining simply takes less time to form and reach equilibrium compared to a thicker one. This analysis only considers the thermal solution using the latent heat

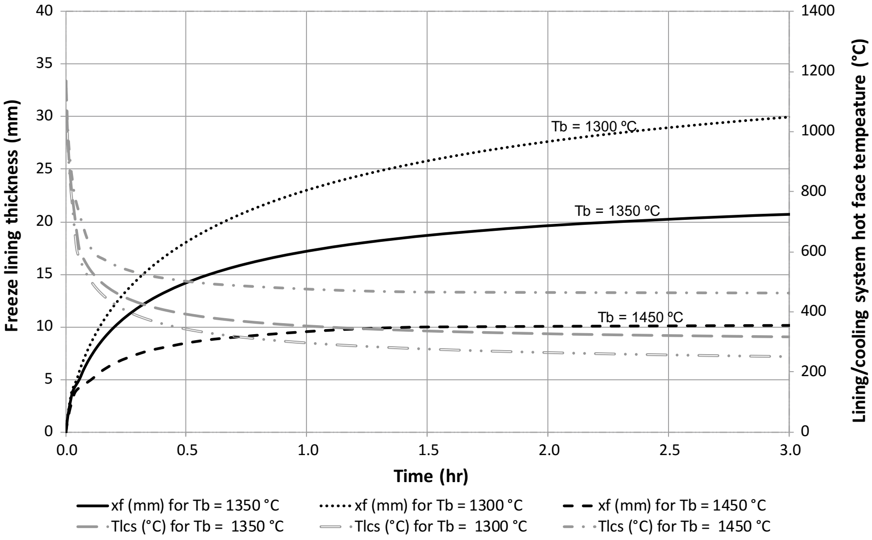

Fig. 3 x_{freeze} and T_{lcs} during freeze lining formation for different values of T_{bath}

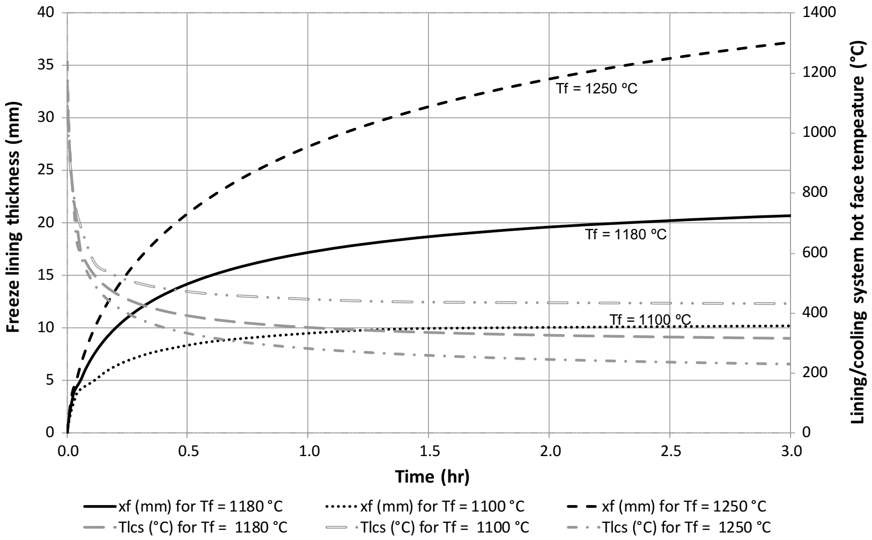

Fig. 4 x_{freeze} and T_{lcs} during freeze lining formation for different values of $T_{freezing}$

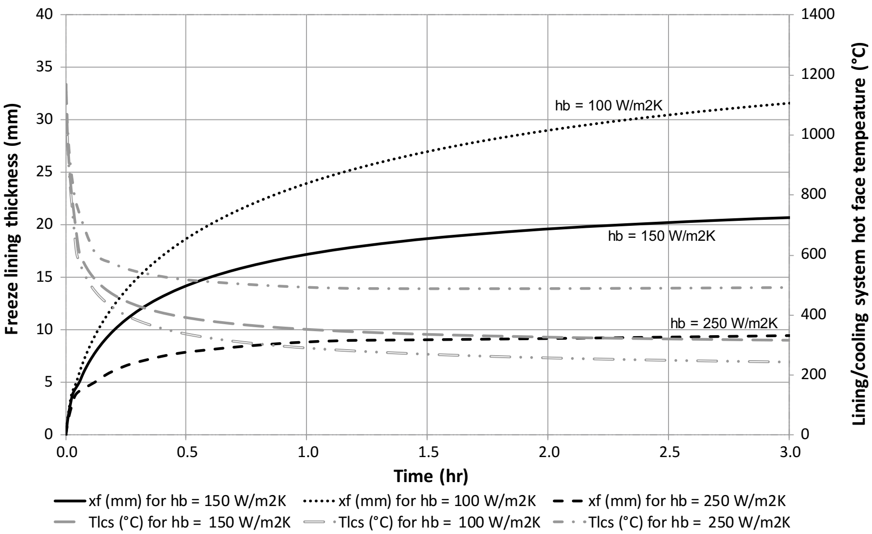

Fig. 5 x_{freeze} and T_{lcs} during freeze lining formation for different values of h_{bath}

of fusion as the rate-limiting variable. It has been shown by Crivits et al. [35] that the freeze lining microstructure development, phase formation and crystallization path may affect not only the final freeze lining thickness, but also the rate of freeze lining formation.

Extreme Operating Conditions and Furnace Cooling Design

As discussed in section "Normal Operating Conditions and Heat Loss", once a freeze lining is established and maintained, the heat loss through the furnace sidewall is a function of the macroscopic process parameters such as bath temperature, slag freezing temperature and those affecting the heat transfer coefficient between the bath and the sidewall. In addition, the microstructure of the freeze lining may affect the heat loss through the furnace sidewall. The heat loss is not a function of the lining/cooling system design once a steady state freeze lining has been established. The same is true for the freeze lining thickness. As shown in Table 1, the freeze lining thickness is more sensitive to the process parameters, slag chemistry and freeze lining microstructure, than the design of the lining/cooling system. The furnace operator, therefore, controls the long-term heat loss and the freeze lining thickness by adjustment of operating parameters and slag chemistry.

However, whereas the normal operating conditions determine the long-term heat losses from the furnace, the furnace campaign life is more a function of the short-term extreme operating conditions [16]. It follows that a design objective for the sidewall lining/cooling system, and the copper cooling elements in particular, should be, first, to extract sufficient heat to establish, re-establish and maintain a freeze lining under all operating conditions, including extreme operating conditions. Second, 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 designs 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.

Tenova Pyromet employs thermal FEA models to evaluate and optimise the design of copper cooling elements considering extreme operating conditions. This method, as well as the subsequent ability of a well-designed lining/cooling system to cope with extreme operating conditions and re-establish a freeze lining has been documented by Joubert et al. [2] for a platinum slag cleaning furnace.

Conclusions

An increasing number of furnaces used for base metal smelting, converting and slag are designed and equipped with sidewall copper cooling elements. The copper cooling elements operate either on their own or in combination with a refractory lining. In all cases, the intent is for the copper cooling elements to reduce the lining/cooling hot face temperature sufficiently to prevent or reduce the wear of the furnace sidewall.

Under steady state conditions, the heat loss through the furnace sidewall is equal to the heat load or input from the furnace bath. Under these conditions, the freeze lining thickness

- Is directly proportional to the freeze lining thermal conductivity
- Increases as the bath superheat decreases due to a decreasing bath temperature
- Increases proportionally even more if the bath superheat decreases due to an increasing slag freezing temperature
- Increases as the bath to freeze lining/sidewall heat transfer coefficient decreases
- Increases as the overall lining/cooling system thermal resistance decreases.

The process parameters (such as bath temperature, T_{bath}, bath to sidewall heat transfer coefficient, h_{bath}.) and slag properties (such as freeze lining thermal conductivity, k_{freeze} slag freezing temperature $T_{freezing}$), have a considerably greater influence on the freeze lining thickness than the lining/cooling system design parameters once a freeze lining has been established and reasonably steady state conditions have been achieved.

Should the freeze lining dislodge completely from the hot face of a well-designed lining/cooling system, the molten slag bath will wash up directly against the lining/cooling system hot face and the freeze lining will begin to reform. As steady-state conditions no longer exist, the heat load/input on the sidewall is no longer equal to the heat output/through the sidewall. The transient sidewall heat balance includes the latent heat of formation or fusion term used to describe the heat removed to form the freeze lining or the heat absorbed to melt the freeze lining over time.

As with steady-state conditions, the freeze lining thermal conductivity, k_{freeze}, significantly affects the freeze lining thickness. The freeze lining thickness approaches its equilibrium steady state value more quickly for lower freeze lining thermal conductivity values than for higher thermal conductivity values. The freeze lining thickness will approach equilibrium more quickly for a higher bath superheat and a higher bath to sidewall heat transfer coefficient because of the lower equilibrium freeze lining thickness associated with a higher superheat.

Whereas the normal operating conditions determine the long-term heat losses from the furnace, the furnace campaign life is determined by the extreme operating conditions. The design objective for the sidewall lining/cooling system, and the copper cooling elements in particular, is, first, to extract sufficient heat to establish, re-establish and maintain a freeze lining under all operating conditions, including extreme operating conditions. Second, 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.

References

1. Burteaux M, Krafft W, Van Laar J, Traice FB, Vecchiola G (1987) Latest development in cooling and refractories of European blast furnaces. Steel Times 492–503
2. Joubert H, Nourse RB, 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: 44th annual conference of metallurgists on nickel and cobalt 2005—challenges in extraction and production, Calgary, Alberta, Canada, pp 19–35
3. Eksteen JJ, Van Beek B, Bezuidenhout GA (2011) Cracking a hard nut: An overview of Lonmin's operations directed at smelting of UG2-rich concentrate blends. Southern African Pyrometallurgy 2011 International Conference, Cradle of Humankind, South Africa, pp 231–251
4. Nelson LR, Stober F, Ndlovu J, De Villiers LPvS, Wanblad D (2005) Role of technical innovation on production delivery at the Polokwane smelter. In: 44th annual conference of metallurgists on nickel and cobalt 2005—challenges in extraction and production, Calgary, Alberta, Canada, pp 91–116
5. Jones RT (2005) An overview of Southern African PGM smelting. In: 44th annual conference of metallurgists nickel and cobalt 2005—challenges in extraction and production, Calgary, Alberta, Canada, pp 147–178
6. Hundermark R, De Villiers B, Ndlovu J (2006) Process description and short history of Polokwane smelter. In: Jones RT (ed) Southern African pyrometallurgy 2006 international conference, Cradle of Humankind, South Africa, pp 35–41
7. Mc Dougall I (2013) Sidewall design for improved lining life in a PGM smelting furnace. J Southern African Instit Mining Metallurg 113:631–636
8. Bryk P et al (1958) Flash smelting copper concentrates. Mining Eng 683–684
9. Yasuda Y, Motomura T, Kawasaki T (2014) Improvements to the operation of the Saganoseki flash smelting furnace. In: Conference of metallurgists
10. Marx F, Shapiro M, Henning B (2010) Application of high intensity refractory cooling systems in pyrometallurgical vessel design. The twelfth international ferroalloys congress. Helsinki, Finland, pp 769–778
11. Bhappu RR, Larson KH, Tunis RD (1994) Cyprus miami mining corporation smelter modernization project summary and status. In: Warren G (ed) EPD congress, pp 555–570
12. Kim MB, Lee WS, Lee YH (2000) The QSL lead slag fuming process using an Ausmelt furnace. In: Dutrizac JE et al (eds) Lead–Zinc 2000, The minerals, metals and materials society, pp. 331–343
13. MacRae A, Steinborn B (2018) Top submerged lance furnace lining cooling system upgrade. Extraction 2018, Ottawa, Quebec, Canada, pp 463–480
14. Viviers P, Hines K (2005) The New Anglo platinum converting project. First extractive metallurgy operators' conference. AusIMM, Brisbane, pp 101–108
15. Nikolic S, Hogg B, Voigt P (2018) ISASMELT™—flexibility in furnace design. Extraction 2018, Ottawa, Quebec, Canada, pp 435–443
16. Joubert H (1997) MEng Thesis: analysis of blast furnace lining/cooling systems using computational fluid dynamics. Rand Afrikaans University (now University of Johannesburg), Johannesburg, South Africa
17. Kyllo AK, Gray NB, Papazoglou D, Elliot BJ (2000) Developing composite furnace module cooling systems. JOM February 2000, pp 66–67

18. Joubert H (2000) Designing for slag freeze linings on furnace sidewalls–an engineering perspective. In: 6th international conference on molten slags, fluxes and salts, Stockholm, Sweden-Helsinki, pp 1–11
19. Shaw A et al (2012) Challenges and solutions in PGM furnace operation: high matte temperature and copper cooler corrosion. In: 5th platinum conference 2012, Sun City, South Africa, pp 193–216
20. Thethwayo BM, Garbers-Craig AM (2010) Corrosion of copper coolers in PGM smelters. In: The 4th international platinum conference, platinum intransition 'boom or bust'. The Southern African Institute of Mining and Metallurgy 2010:187–193
21. Verscheure K, Kyllo AK, Filzwieser A, Blanpain B, Wollants P (2006) Furnace cooling technology in pyrometallurgical processes. Sohn International Symposium, vol 4, TMS, pp 139–154
22. Campforts M, Jak E, Blanpain B, Patrick W (2009) Freeze lining formation of a synthetic lead slag—part 2: thermal history. Metall Mater Trans B 40:632–642
23. Campforts M, Blanpain B, Wollants P (2009) The importance of slag engineering in freeze lining applications. Metallurg Mater Trans B (2009) 40: pp. 643–655
24. Scholey KE, Richards GG, Samarasekera IV (1991) Heat-transfer phenomena in water-cooled zinc-fuming furnace jackets. Metall Trans B 22B:163–175
25. Kang S (1991) A model study of heat transfer and fluid flow in slag-cleaning furnaces. PhD thesis, University of Missouri-Rolla
26. Mills KC (1988) Thermal conductivities of liquid slags. In: 3rd International conference on molten slags and fluxes, June 1988, pp 229–234
27. Mills KC (2011) The estimation of slag properties. Short course presented as part of Southern Africa Pyrometallugy 2011 conference
28. Bezuidenhout JJ, Eksteen JJ (2009) Bradshaw SM (2009) CFD modelling of molten matte and slag flows in a circular three-phase smelting furnace. Prog Computat Fluid Dynam 9(6/7):316–324
29. Joubert H, Nikolic S, Bakker ML, Mc Dougall I (2016) Tenova Pyromet—cooled copper furnace elements. Copper 2016, Kobe, Japan, PY14–3, pp 955–965
30. Kennedy MW, Nos P, Bratt M, Weaver M (2013) Alternative coolants and cooling system designs for safer freeze lined furnace operation. Printed Ni–Co 2013:299–314
31. Kennedy MW, MacRae A, Jones RT, Kolbeinsen L, Nos P, Filzwieser A (2015) Some considerations for safer furnace cooling. As presented at COM 2015, Toronto, Canada, published by Canadian Institute of mining, metallurgy and petroleum
32. Kennedy MW (2012) Electric slag furnace dimensioning. In: Downey JP, Battle TP, White JF (eds) International smelting technology symposium: incorporating the 6th advances in sulfide smelting symposium. TMS, Orlando, FL, pp 279–290
33. Kennedy MW (2013). Slag furnaces—some issues for optimal design and operation. In: Proceedings of conference of metallurgist, Ralph Lloyd Harris memorial symposium. Montreal, QC, pp 411–426
34. Nelson LR, Hundermark RJ, Van der Merwe K (2015) Observations on the impact of furnace dimensions and power density on taphole integrity. In: Proceedings of the conference of metallurgists, COM 2015, Toronto, Canada, Paper no. 8877
35. Crivits T, Hayes PC, Jak E (2017) An investigation of factors influencing freeze lining behaviour. In: Mineral processing and extractive metallurgy IMM transactions section C, September 2017, pp 195–209
36. Crivits T, Hayes PC, Jak E (2018) Investigation of the effect of bath temperature on the bath-freeze lining interface temperature in the CuO_x–FeO_y–MgO–SiO_2 system at copper metal saturation. Int J Mater Res 109(5):386–398
37. Crivits T, Hayes PC, Jak E (2018) Freeze linings in the Al_2O_3–CaO–SiO_2 system. International Journal of Materials Research, 109, 2018, 7 (May), pp. 638–653