DEVELOPMENTS IN COPPER COOLER DESIGN FOR PYROMETALLURGICAL APPLICATIONS

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ABSTRACT

The use of copper cooling elements to enhance refractory lining life in pyrometallurgical vessels is common in modern furnace design. Copper elements typically incorporate a base panel with cast in cooling passages and an integral extended surface (formed of pins, fins or similar) onto which suitable refractory material is cast. The metallic, conducting parts are located towards the cold face of the lining, with the refractory material interposing between the coolers and the process. The coolers are designed to arrest wear of the refractory material by freezing a layer of slag or partially reacted material onto the hot face, thereby rendering the lining inert to further attack [1]. These coolers have achieved success in new furnaces and relining of existing vessels.

The freeze layer is prone to mechanical damage during operational and process instability. The coolers must be capable of extracting the additional heat flux under upset conditions to facilitate rapid self-repair of the freeze layer and prevent further refractory wear in the intermittently exposed areas. However, operational experience has shown that the high heat flux capabilities of the copper coolers have some disadvantages, especially in processes producing vapours which form corrosive compounds when condensing onto the cold surfaces of the coolers. When corrosive conditions develop, the entire composite will fail due to loss of structural integrity, and as a result of leaks from the cooling water passages.

This paper describes recent developments in the approach to the design and manufacture of copper cooler panels customized to achieve specified heat fluxes and temperature profiles, thereby reducing the formation of corrosion mechanisms in applications with corrosive gaseous environments and enhancing refractory lining life. Condensation formation prevention is achieved by adjusting the geometry of the cooler and selection of suitable materials of construction.

1. INTRODUCTION

The refractory lining of a pyrometallurgical reactor is exposed to conditions contributing to wear mechanisms, which may be active in different combinations simultaneously, some of which are listed below.

- Periodic exposure to hot face temperatures above the service limit of the refractory
- Thermal stress cracking as a result of exposure to sudden temperature excursions such as arc flare and start-up after prolonged process interruptions, or metal infiltration combined with thermal cycling
- Exposure to corrosive slag and metallic phases in the molten bath, and on freeboard walls washed by particles ejected by arc spatter or feed splash which results in wear of refractory material by continuous dissolution into the unsaturated melt constituents
- Corrosion/ modification of the refractory micro-structure by gaseous by-products of the process.

When the above factors are sufficiently severe, the refractory lining will fail prematurely resulting in loss of production and additional costs of relining.

Suitable ceramic solutions by selection of chemically compatible refractory material are available in some cases. However, there are several instances (eg processes involving the production of fayalitic slag) where ceramic solutions with suitable chemical resistance have proved elusive. Operational approaches involving slag chemistry adjustments have also achieved a measure of success, but not entirely without some compromise between production costs for fluxes and losses in recovery. Refractory cooling systems have proved to be successful in extending refractory life by facilitating operation with a lining of products and by products which are frozen onto the face of the refractory material exposed to the process. [1], [2], [3]

In the upper freeboard, it is generally not possible to form a freeze lining, as a limited quantity of molten material is able to reach these areas. Accretion layers formed of partially reacted materials and fines in the feed can protect these areas. This renders the lining chemically inert to corrosive mechanisms, reduces the average operating temperature, and attenuates the effect of temperature excursions. The lining is sustained by matching the heat extraction capabilities of the coolers to the convective, radiative and conductive heat transfer from the process. In addition, the coolers require a substantial heat transfer margin above this continuous rating to facilitate the self healing of the freeze lining when parts are lost under process upset conditions or structural instability of the relatively inhomogeneous and brittle freeze layer. The cooling systems typically incorporate the components listed below:

- Copper base panel with water cooling passages
- Extended copper surface integral with the base panel to facilitate bonding with the intermediate refractory layer, and enhance slag / accretion retention
- Intermediate layer of refractory material (typically castable) which acts as a heat flux moderator whilst equilibrium is achieved between the residual refractory thickness and the freeze lining thickness under steady state operating conditions

Some cooling systems are constructed of copper blocks with water passages located towards the cold face. These are installed between brick courses in a suitable pattern to achieve the required heat flux associated with the process.

The improvements in lining performance achieved with the freeze lining approach have been well documented in literature on this subject [2]. However, operation with refractory cooling systems has not proved to be a universal panacea.Certain processes (eg flash smelting of sulphide ores, ores containing traces of halogens) produce gaseous by-products, which are corrosive to copper when they condense. The corrosion is normally most severe at the point of incipient condensation because of the favourable reaction kinetics of hot corrosive liquids in contact with the extended metallic surfaces. Under these conditions, the lining system begins to fail due to loss of structural integrity of the underlying metallic conductive matrix, and formation of potentially explosive water leaks into the process.

Figure 1: Corroded copper block cooler in sulphuric/ sulphurous acid condensing environment

Areas above the slag line are more likely to be exposed to gaseous by-products, and must be capable of resisting corrosion by both solid-gas reactions, and by condensate formation. The heat flux required to cool the refractory materials and maintain self-protective layers above the slag line and in the upper freeboard is inherently lower than refractory material in contact with the molten bath. The coolers in these areas can therefore be operated at higher temperatures to prevent condensation.

2. PROBLEM STATEMENT

Develop a general refractory cooling system design methodology which simultaneously optimises refractory life and prevents corrosion of the cooling element metallic components by gaseous by-products, thereby ensuring that the security against refractory failure does not compromise metallic component life and vice versa.

3. APPROACH

Four alternatives are investigated in this paper to optimise designs capable of eliminating or reducing corrosion of copper initiated by over-cooling. These are based on solutions which moderate the thermal gradients and achievable heat flux to limit the areas of the cooler operating below the due point of vapours present:

Option 1	Selecting materials or metallic composites to obtain lower thermal conductivities than a pure copper system
Option 2	Configuration of the metallic component geometry to achieve the correct balance between length of conducting path and cross sectional area along the path
Option 3	Balance conducting area against convective heat transfer area in the water passages (but ensure that water does not boil)
Option 4	Locate cold surfaces beyond the point at which gaseous by-products can leave the process and vent to atmosphere, thereby limiting the amount of condensate formation. This is typically achieved by increasing the length of the metallic components and locating the cooling passages outside the vessel so that condensable gases escape before condensing

The following strategies are also considered to be viable, but will not be dealt with further in this paper:

- Manufacture the metallic parts of the cooling system using corrosion resistant materials (eg stainless steel). This was deemed not to have sufficient universal application because each situation would require specific material selection, suitable manufacturing technology, and inevitably result in a compromise between thermal conductivity and corrosion resistance. A single material exhibits different corrosion resistance across ranges of chemical concentrations and temperatures, meaning that in a particular application, whilst one area of the cooler may be exposed to a temperature and a pH that it can resist, another area may be more severely affected.
- Operate the furnace at internal freeboard pressures to avoid gaseous ingress into the refractory matrix. This is difficult to achieve in practice without inducing oxygen flow into the furnace, which will cause other operational problems including premature combustion of combustible gases.

A simple one-dimensional model was developed to demonstrate the effects of adjusting variables available to the refractory cooling system designer in the freeboard area of a pyrometallurgical process for the first 3 options. The model is a pin comprised of a three conduction zones connected in series with a convective water film on the cold face and a convective gas film on the hot face. The first two zones of the pin are assumed to be metallic, and were provided to simulate the effect of changes in conductivity and cross sectional area in the metal parts of the cooling system. The third zone nearest the hot face simulates the effect of a thin layer of freeze lining or accretion build-up, and is necessary to ensure that realistic temperatures for copper based systems are estimated. In addition to the heat convected by the process to the hot face, the model makes provision for heat transfer by radiation. The model was set up as an Excel ® spreadsheet and the 'Goal Seek' function used to solve the non-linear system of equations to determine the equilibrium heat flow in the process-hot face and hot face-water paths as follows

Figure 2. Illustrative one dimensional pin model

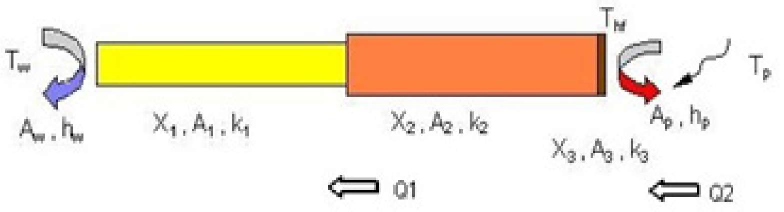

Figure 2: Illustrative one dimensional pin model

$$Q_1 = (T_{hf} - T_w)*(1/(A_w h_w) + X_1/(A_1 k_1) + X_2/(A_2 k_2) + X_3/A_3 k_3)^{-1}$$

$$Q_2 = (T_p - T_{hf})*(A_p h_p) + \mathbf{e}\,\mathbf{s}\,A_p*(T_p^4 - T_{hf}^4)$$

Solve for T_{hf} so that $Q_1 = Q_2$

Where (in compatible SI units):

Q_1 = Heat conducted from hot face to water
Q_2 = Heat transferred by convection and radiation from process to hot face
A_w = Area for convective heat transfer into water
A_p = Area for convective and radiative heat transfer from process to metallic pin
h_w = Convection film coefficient, water side
h_p = Convection film coefficient, process gas side
X_i = Length of each conduction zone
A_i = Area of each conduction zone
k_i = Thermal conductivity of each conduction zone
e = Surface emissivity, assumed to be 0,9
s = Stefan-Boltzmann constant ($5{,}67*10^{-8}$ W/m².K^4)
T_p = Process temperature (set to 1500°C)
T_{hf} = Hot face temperature (by iterative solution)

T_w = Water temperature (set to 25°C)

The temperature distributions of the scenarios investigated are shown in Figure 3. below.

Explanation of legend in Figure 3:

Base Case	Material 1 = Copper, Material 2 = Copper, Material 3 = accretion layer. All conductive areas equal, Water passage surface area = 150 % of pin area
Option 1	Base case, but with zone 1 Aluminium Bronze Alloy (ABS, k1 = 80 W/m°C)
Option 2	Base case, but with reduced area of Material 1, or increased area of Material 2
Option 3	Base case, but with water area = 50 % of pin area
Condense	Vapour condensate line, 165°C (Typical for sulphuric acid)

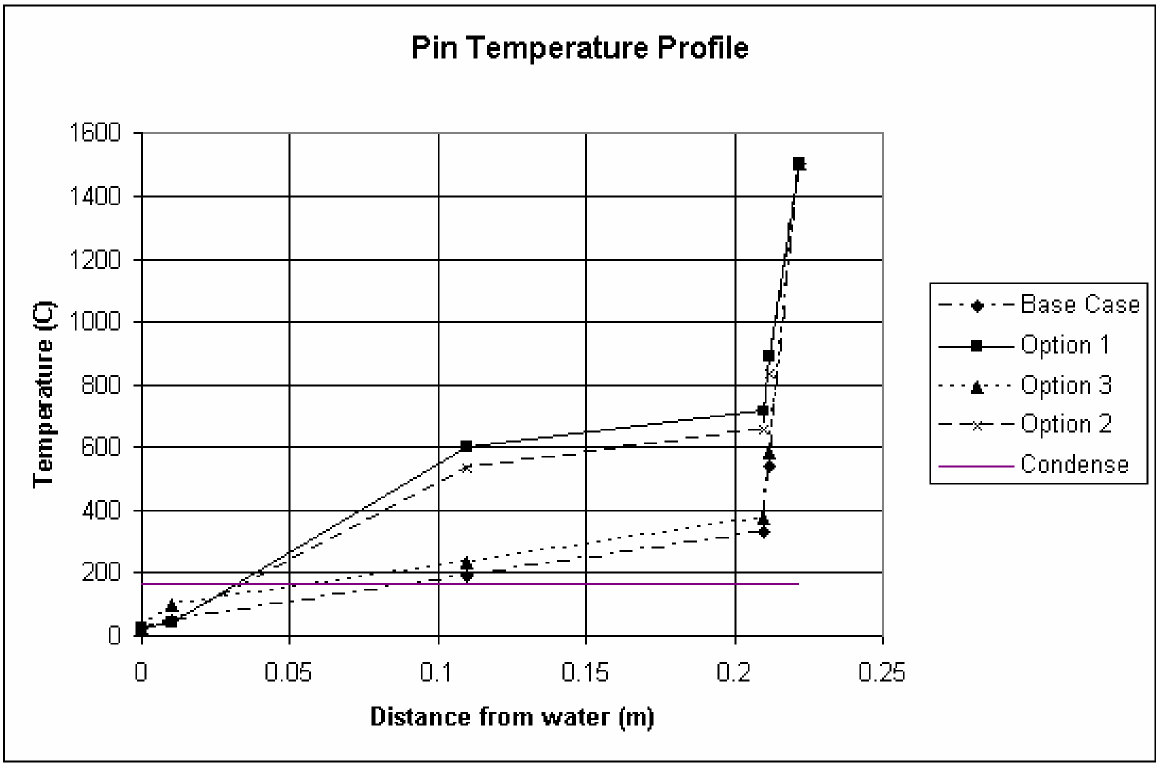

Figure 3: Results of changes in pin design parameters

The model demonstrates that all the scenarios are effective in moving the intersection point between the thermal gradient and the condensation line back towards the water passages when compared to the base case, indicating that less pin surface area is exposed to condensate formation.

The weakest response is obtained by reducing the water passage area. The effect is proportional to the reduction in area, but there is a distinct limit to its extent. This is reached when film boiling occurs, causing a significant reduction in the film coefficient and an unstable temperature at the interface between the pin and the water-cooled passage. Under extreme conditions sufficient steam will form in the passage, restricting the flow of water, and potentially causing an explosion. This is generally not the preferred method for avoiding surface condensation on the pin.

Reducing the thermal conductivity of the pin zone closest to the water passage produces a significant effect. In the model, this would be equivalent to substituting ABS (aluminium bronze alloy) for copper. A similar but more limited effect would be obtained by manufacturing the cooling passage walls of schedule 80 stainless steel tubing. Whilst both of these alternatives are theoretically possible, they represent challenges to the casting process to ensure that sufficient thermal bonding is obtained at the copper interface to commercially manufacture coolers which perform consistently.

A similar result to the reduced thermal conductivity model is obtained by reducing the area of the portion of the pin closest to the water passage. This enables the designer to incorporate a variable thermal resistance in the configuration of the conducting portion of the refractory cooling system to adjust the intersection point with the condensation isotherm. The achievable effect is limited by the melting point/ oxidation temperature limit of the pin tip (eg copper exhibits increased oxidation rates at temperatures above 525 oC). The cooler geometry is conveniently manufactured using conventional foundry technology, and no interface issues involving different materials have to be resolved. Bateman have recently implemented this strategy to design replacement equipment for coolers in a duct transporting a high temperature SO2 gas stream. The original coolers were badly corroded by sulphuric/ sulphurous acid on surfaces adjacent to the water cooling passages, maintained at temperatures below the acid vapour dew point.

Option 4 (moving the cooling passage further from the process by increasing the length of zone 1) has an analogous effect to reducing the area of this zone, but this was not modelled to avoid confusion in the temperature gradient plot. In principle, the variable being modelled in both Option 3 and 4 is the thermal resistance l1/k1A1. A proportional increase in the thermal resistance of this zone can be obtained by reducing A1 or increasing l1. This approach has the added benefit of allowing condensable gases to escape from the system before they contact areas of the copper cooler below the condensation temperature. However, the option can only be implemented if the furnace shell can be designed with the necessary openings for the coolers to extend to the outside, and extra attention is required to compensate for vertical differential expansion between the refractory lining and the shell.

The one dimensional model presented above is for illustrative purposes, and is not the design tool used for commercial applications. In practice, the complexity of the real world can only be modelled using Finite Element Analysis (FEA) and Computation Fluid Dynamics (CFD) software applications. The basic geometry of the cooler is first determined from the furnace lining layout, installation and maintenance constraints, and primary heat flux considerations. An FEA model is developed in parallel, frequently making use of para-solid object exchange capabilities between suitable CAD and analytical packages. This enables the following to be evaluated:

- Effect of refractory on the hot face under various worn lining scenarios
- 3-dimensional thermal diffusion
- Stress fields coupled to thermal gradients and different material properties throughout the system
- Conjugate heat transfer using CFD in cases where the temperature rise along the water passages is significant or the water passage layout is complex

The designer must be aware that solutions involving temperature gradient adjustments induce thermal stresses due to non-uniform thermal gradients. To illustrate one of the limitations of this design approach, consider a bar of uniform cross sectional area, unrestrained against thermal expansion and subjected to a 1 dimensional constant thermal gradient perpendicular to the axis of the bar. The bar bends towards the cold face, but no internal stress field is induced as shown by the coupled stress and isotherm plots in the top of Figure 4. below. If the thermal gradient is not constant, stresses develop in the bar as the hotter regions try to expand at a greater rate than that permitted by the colder regions as contrasted in the bottom of Figure 4. below.

A similar phenomenon develops in the vertical axis of a cooler structure when the thermal gradient in the horizontal axis is altered by varying the thermal resistance as described above. The stresses are amplified by the stress concentration at the change in area. The FEA results of a copper cooler system designed for an existing rectangular off gas duct are presented as an illustration. The cooler geometry was iteratively refined to achieve the required heat flux moderation and temperature gradient within the physical constraints of the installation, availability of cooling water and thermal expansion compatibility with associated support structures. The coupled isothermal - stress field through a critical cross section of the resulting 3 dimensional model is shown in Figure 5. below.

A summary of the copper cooler design approaches investigated which limit the condensation of corrosive vapours together with their advantages and disadvantages are listed in the table below.

4. CONCLUSIONS

High heat transfer capacity, copper based refractory cooling systems are susceptible to damage in the presence of condensable, corrosive vapours, particularly in the freeboard of a pyrometallurgical reactor. A simple mod-

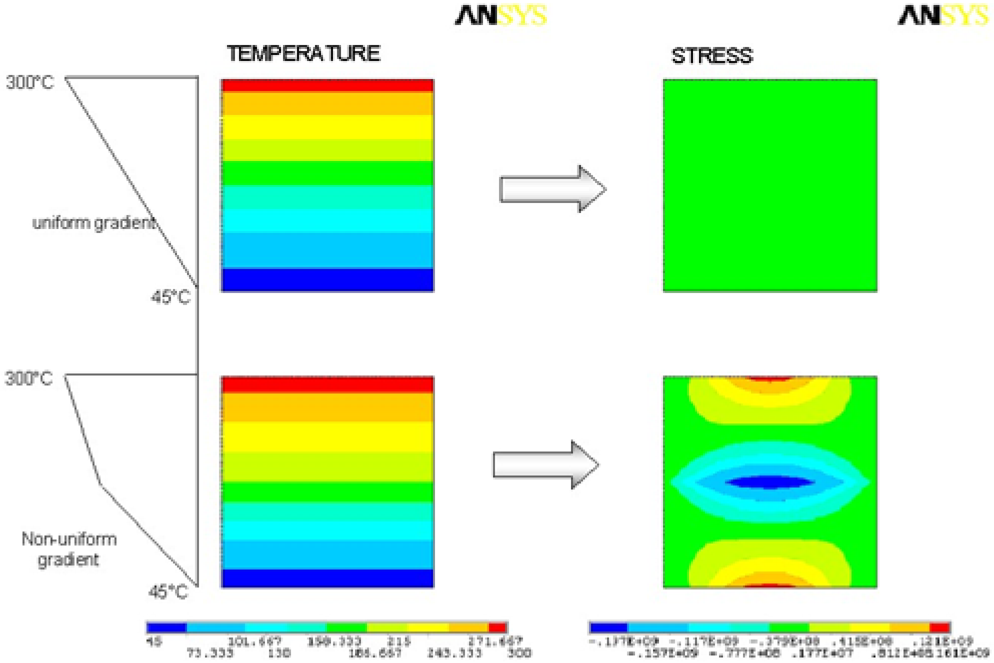

Figure 4: Coupled temperature and stress fields of a free standing prismatic steel bar analysed using 2D plain stress elements.
Top:Uniform temperature gradient does not induce stress under thermal deformation.
Bottom:Non-uniform temperature gradient induces stress.

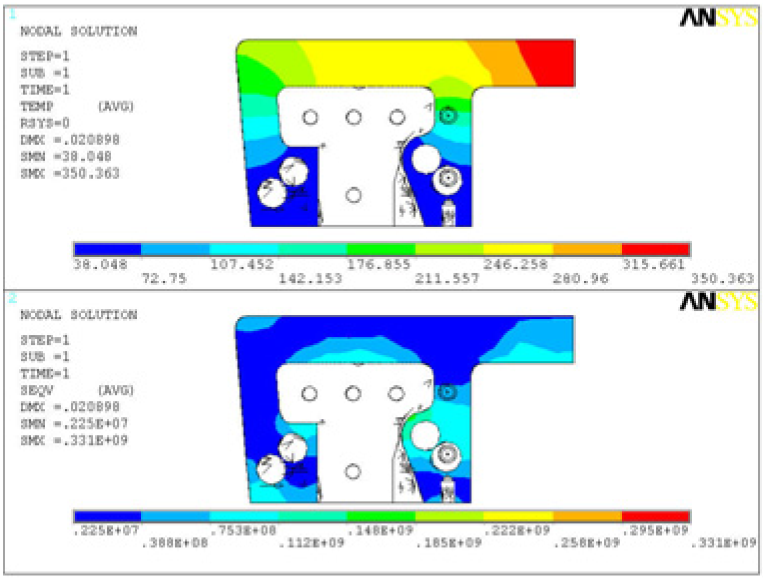

Figure 5: FEA results through a critical cross section of a copper cooler for a gas duct wall
Top:Isothermal plot
Bottom:Coupled stress field plot

el has been presented to demonstrate alternative design strategies to improve the life of cooling elements operating under these conditions by reducing the surface area of the metallic parts exposed to condensation.

Approach	Advantages	Disadvantages
Reducing water side area (smaller/ less passages)	Easy to implement Reduced cooling water requirements	Limited change in temperature gradient Danger of film boiling
Metallic composites	Easy to tailor required temperature gradients	Complex manufacturing technology Thermal bonding at interfaces Melting and oxidation limitations
Thermal resistance adjustment	Easy to implement using existing foundry practice	Differential thermal expansion stresses Melting and oxidation limitations
Location of cooling passages outside process	Corrosive vapours escape before condensing Thermal induced stresses eliminated or limited	Interruptions in shell structure Vertical expansion compensation

Satisfactory improvements are obtained by increasing the thermal resistance of the portion of the metallic parts closest to the water. Reducing the pin cross sectional area along part of conducting path, or lengthening the pin and locating the water passages outside the reactor are currently preferred because these designs are conveniently implemented using existing foundry practices. The increase in the thermal resistance is limited by the necessity to satisfy the required heat capacity of the system for freeze lining formation, and the melting or oxidation temperatures of the materials of construction.

FEA modelling is required to confirm the effects of worn refractory linings, 3D thermal diffusion and stresses resulting from the deliberately induced non-uniform thermal gradients.

5. FURTHER WORK

The following aspects need to be investigated in order to advance the development of this technology:

- Manufacturing method for coolers constructed of metallic composites
- Furnace pressure control to inhibit diffusion of condensable gases into refractory matrix
- Monitoring of commercial units currently in operation, and field test work of trial units

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