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CFD MODELLING ASSISTANCE FOR THE DESIGN OF ELECTRIC FURNACE SLAG TAPHOLE BREAST PLATES

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ABSTRACT

During 2005 a safety issue arose on the BHP Billiton Olympic Dam electric slag cleaning furnace, where the slag tapholes would ‘self tap’ or open unexpectedly. Investigations identified that the cause of these events was wear to the taphole and castable refractory. An additional replaceable copper cooling element or ‘breast plate’ was selected as the solution to address the problem. This paper outlines the design process that was assisted by the use of CFD models of the taphole - modelling temperature, slag solidification and flow. Boiling curves were also used to determine the safety of the various designs considered.

NOMENCLATURE

f_L	Liquid mass fraction (-)
K_0	$1*10^{-10}$ (m^2)
LiqFrac	Liquid Volume Fraction (-)
S_k	Turbulence Kinetic Energy Source (m^2/s^2)
S_m	Momentum Source (kg m/s)
S_ε	Turbulence Energy Dissipation Source (m^2/s^3)
SolFrac	Solid Volume Fraction (-)
T	Local fluid temperature (K)
T_{liq}	Liquidus Temperature (K)
T_{sol}	Solidus temperature (K)
U	Fluid Velocity (m/s)
U_S	Fixed Solid Velocity (m/s)
μ_L	Liquid viscosity (kg /m s)

INTRODUCTION

The slag tapping block design for the electric furnace is shown in Figure 1. The taphole consists of a 154 mm thick water cooled copper block with a castable refractory backing to take the design taphole length to approximately 550 mm. The design taphole diameter is 70 mm.

A mudgun is used to close the tapholes at the end of the tap by filling the tapping channel with clay, which subsequently bakes in the hot furnace environment to form a solid plug in the hole. The hole is opened again at the next tap using a tapping drill to drill through the baked clay plug to the molten bath. Consumable steel oxygen lances are used to burn/melt out the clay plug when the drill is unavailable or unable to open the hole.

Since installation in 2003, the taphole diameter through the water cooled copper block has become enlarged due to damage caused by lancing and drilling, and the castable refractory has been lost through wear and tear caused by the flowing slag as well as impact from the tapping drill.

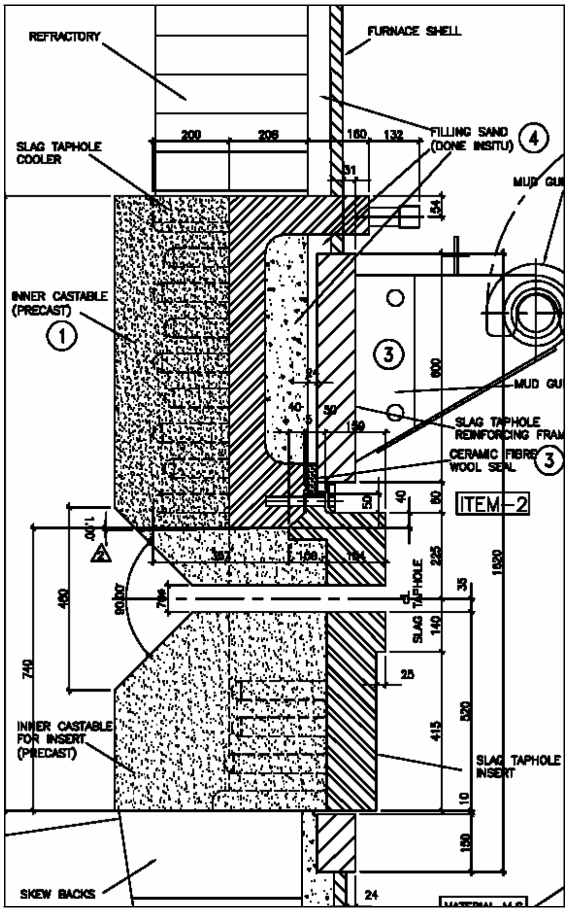

Figure 1: Vertical Section through Electric Furnace at Slag Tapholes

Without the castable, there is no structure with which taphole clay can bond, and the water cooled copper that remaines is too cool to bake the clay and form the hard plug. In the worn state, the tapholes are being kept closed in between taps by frozen slag in contact with the water cooled copper rather than a baked clay plug.

Self tapping events occurred when the slag in contact with the copper block became molten and the clay plug is insufficient to plug the taphole. This could be brought about by an excursion in process temperature or by a change in process conditions and slag properties.

The primary issue with self tapping is the molten material hazard posed to Operators performing cleaning and maintenance duties around the tapholes in between taps. Self tapping also impacts copper recovery in the furnace, as the slag exits before being completely processed.

In non-ferrous smelters, taphole wear is typically managed through replacement of the cooler blocks or taphole refractories. However, the slag tapping blocks, which were installed as part of the 2003 electric furnace upgrade to CFM cooling element technology, are an integral part of the electric furnace that have never been removed. The electric furnace CFM coolers are performing well, and it is anticipated that a furnace re-line will not be required for some time. It was anticipated that removing the slag tapping blocks for maintenance would be a long, involved and somewhat dangerous job to undertake.

It was decided to mitigate the self tapping by fitting an additional water cooled copper 'breast plate' to the cold face of the tapping blocks. This would provide additional cooling to keep the slag in the taphole frozen in between taps and extend the length of the tapholes. Also, the additional blocks would provide a means to maintain the electric furnace slag tapholes which did not previously feature any changeable parts.

DESIGN PROCESS

The original design proposed for the breast plates was made from 75 mm thick copper billet and featured a 32 mm diameter straight horizontal water passage centred 121 mm vertically above the centreline of the taphole.

CFX 5.7 was used to investigate the steady state temperature distribution in the proposed breast plate and tapping block arrangement, under the most extreme tapping conditions. The criteria for a safe design was one in which the conditions at the cooling water passage wall were consistent with forced convection heat transfer and did not drift into regions where boiling could occur.

The simulation identified a hot spot on the surface of the water passage, which was not consistent with convection. There was concern that this could potentially lead to film boiling. If film boiling occurs and cooling is lost, the element can overheat and fail. This presents the opportunity for contact between water and molten material. This can lead to explosions and is one of the most significant risks carried by modern smelters, the result is aptly described as 'catastrophic' by Mucciardi et al (2000).

The design flaw was the proximity of the water passage to the tapping channel. However, the horizontal water passage could not be raised because of the location of the mounting bolts in the breast plate, which were dictated by the existing fixing points on the tapping block. An inverted V shaped water passage was identified as a means to increase the distance between the water passage and the tapping channel without encroaching on the bolt holes.

A simulation of this arrangement demonstrated that the inverted V shaped passage was an improvement. However, boiling could still not be ruled out in the breast plate.

At this point, assistance was sought from Bateman Minerals & Metals Limited, who had been involved in the existing electric furnace slag tapping block design. Bateman suggested increasing the thickness of the breast plate above the tapping channel to accommodate a larger (50 mm) diameter water passage, while retaining the 75 mm thickness at the tapping channel. Thereby retaining the same surface area for heat transfer from the slag, but increasing the surface area for heat transfer to the cooling water.

Under the most extreme tapping conditions, the conditions at the water passage wall were consistent with forced convection heat transfer. Accordingly, the Bateman Design was approved for installation. Bateman also assessed the final design using their established FEA modelling techniques, completed the detailed design work and prepared the construction drawing.

MODELLING TECHNIQUE

Geometry

Isometric views of the external and internal details of the model are shown in Figure 2 and Figure 3. The model comprised of the relevant breast plate design and the water cooled copper part of the existing slag tapping block. The wear profile in the tapping channel of the existing tapping blocks was characterised by direct measurement during a furnace maintenance drain and incorporated into the model. The breast plates were modelled in 'as new' condition, ie. without any wear in the tapping channel.

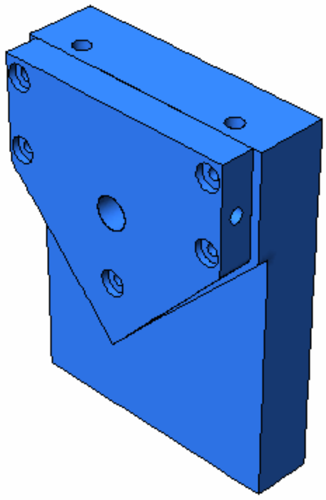

Figure 2: Geometry of copper coolers. Original breast plate in foreground, tapping block behind.

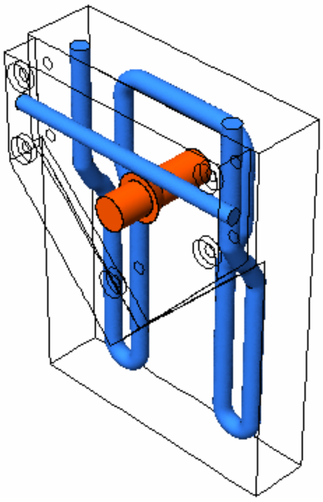

Figure 3: View of geometry showing internal detail for the original breast plate case. Water passages shown in blue, tapping channel shown in red. Note funnel shaped wear profile at cold face of rear tapping block.

The cooling passages in both blocks were meshed so that the water flow through the blocks could be modelled.

This allowed the local wall temperature to be calculated rather than inferred by a boundary condition. Modelling the water flow also provided a route to validate the model based on the total heat transfer through the water circuit.

Material Properties

The tapping block and breast plate were modelled as pure copper with properties evaluated at 25°C from data in Perry & Green (1998). The density of copper decreases with increasing temperature due to thermal expansion effects. However, between room temperature and the melting point the density change is only 5%, so this effect was omitted from the model.

Low temperature thermal properties were used in order to calculate the most extreme temperature distribution in the system for the given conditions. Between room temperature and the melting point, the heat capacity of copper increases and thermal conductivity decreases by approximately 20% and 15% respectively. The resultant thermal diffusivity decreases by 30% over this range.

The copper coolers are prepared from phosphorous deoxidised copper. Data from the Copper Development Association (2006) shows that the phosphorous addition effects an approximately 15% reduction in the electrical and thermal conductivity. This effect was also omitted from the model to be consistent with calculating the most extreme temperature distribution.

The cooling water was modelled as pure water with properties evaluated at 25°C, also from data in Perry & Green (1998). The decision was taken to not use temperature dependent data as the key properties do not change significantly between 0°C and 100°C.

The slag flowing through the taphole was modelled as a fluid with the following properties: density 3800 kg/m^3, viscosity 0.25 Pas, thermal conductivity 1.8 W/mK and a heat capacity of 0.35 cal/gK.

For the solidification model, the slag liquidus was set to 1150°C, the solidus to 1100°C, and the latent heat of fusion to 110 cal/g°C.

All slag properties used in the model were deduced from data of Naumann et al (1976) with the exception of the heat capacity, which was deduced from data in Perry & Green (1998), and the viscosity that was taken from Ajima et al (1995).

Although data on the density of solid slag was available, the density of solid slag was set to the same value as liquid slag to simplify the model by eliminating solidification shrinkage. The heat capacity and thermal conductivity of the solid slag were also set to identical values as the liquid slag. However, this was due to a lack of superior data.

CFD Models

The CFX-5 Solver was used to generate steady state solutions for momentum, energy and turbulence. The copper blocks were modelled as conducting solids. The cooling water in the two blocks was modelled using the thermal energy and k-ε models. The slag in the tapping channel was also modelled using the thermal energy model and the solidification model detailed below.

Slag Solidification Model

Solidification can play an important role in the slag tapholes. If a frozen layer is maintained in the taphole during tapping, this would significantly decrease the heat loads on the water cooled blocks. The technique of MacIntosh et al (2003) was implemented to investigate whether it was likely that a solidified layer would be maintained in the tapping channel. A brief description of the model is given here.

The slag was described as a multi-component fluid consisting of two components, one having the properties of solid slag and the other of liquid slag. The volume fraction of the component with liquid properties in the fluid was related to the fluid temperature according to:

$$LiqFrac = \begin{cases} 0 & if \quad T < T_{sol} \\ \dfrac{T - T_{sol}}{T_{liq} - T_{sol}} & if \quad T_{sol} \le T \le T_{liq} \\ 1 & if \quad T > T_{liq} \end{cases}$$

As the fluid consists of only two components, the volume fraction of the component with solid properties is given by:

$$SolFrac = 1 - LiqFrac$$

For material in the 'mushy region' (ie. that being of temperature between the liquidus and the solidus), the multi-component fluid model will calculate mass averaged properties for the fluid. However, as the density, heat capacity and thermal conductivity of the solid slag were set to identical values as the liquid slag, this was of no consequence in this particular exercise.

The latent heat effects of solidification/melting were incorporated into the model by offsetting the reference enthalpy for the liquid component of the multi-component fluid from that of the solid component by an amount equivalent to the latent heat.

To account for the resistance to flow and the damping of turbulence in the mushy region, Darcy source terms were added to the momentum and turbulence equations. The form of the terms is given below:

$$S_M = \frac{\mu_L}{K_0}\frac{(1 - f_L)^2}{f_L^3}(U - U_S)$$

$$S_k = -\frac{\mu_L}{K_0}\frac{(1 - f_L)^2}{f_L^3}k$$

$$S_\varepsilon = -\frac{\mu_L}{K_0}\frac{(1 - f_L)^2}{f_L^3}\varepsilon$$

To prevent division by zero errors in the code these terms were bounded to effect damping when the liquid mass fraction tends to zero. The fixed solid velocity (U_s) was set to zero here, as the solid in the taphole would stop flowing. The terms in the turbulence equations were implemented in a way that the turbulent diffusion of heat became negligible compared with conduction in the solidified slag.

Water Boiling Model

The critical criteria for film boiling in a particular system are a function of the geometry, pressure, flowrate, bulk fluid temperature and the fluid involved.

Marshall et al (2001) developed an integrated model that calculates Nukiyama boiling curves from the following established heat transfer correlations:

- Sieder-Tate (for forced convection);
- Bergles-Rohsenow incipient boiling correlation;
- Bergles-Rohsenow partial nucleate boiling correlation;

- Araki correlation (for fully developed boiling);
- Tong-75 critical heat flux correlation; and
- Marshall-98 correlation (for film boiling).

Each correlation was selected by Marshall et al (2001) based on comparison with temperature measurements made at the wall of a cylindrical water passage in a copper block that was heated from one side at high heat fluxes.

Heat flux and temperature data calculated by the CFX model at the cooling passage wall was compared with Nukiyama boiling curves prepared using the model of Marshall et al (2001) to determine if conditions in the breast plate were consistent with forced convection.

Boundary Conditions

Boundary conditions were set to reflect the most extreme tapping conditions. Dirichlet boundaries were defined for the tapping channel inlet as well as the cooling water inlets in the breast plate and tapping blocks.

The flow rate of slag was deduced from the time taken to fill a slag pot of known volume from the most worn tapping block at maximum bath level. The slag temperature was set to 1290°C which is the top of the operating range.

The cooling water velocity in the breast plate and tapping block was set to 1.8 m/s, which based on the supply flow to the existing electric furnace slag tapping blocks. The cooling water supply temperature was set to 35°C based on plant data.

The back of the tapping block was modelled as a wall with an incident heat flux of 88 W/m^2 to simulate heat transfer from the bath. The bath heat flux value was calculated from thermocouple measurements in cooling elements in the vicinity of the slag tapholes.

The top, bottom, sides and external surfaces of the model were modelled as adiabatic walls.

Model Validation

To verify the modelling technique for use in the design process, the model was run without the proposed breast plate present. This simulated the slag taphole arrangement that existed at the time, for which plant monitoring data was available. The simulation predicted a rise of 6°C in the bulk water temperature across the tapping block. Plant data indicated that the bulk water temperature rise across the slag tapping blocks during tapping could be as high as 5°C, thus indicating that the heat loads calculated by the model for the scenario of the most severe tapping conditions were not unrealistic.

RESULTS

A plot of the water passage wall temperature calculated by the model for the original breast plate design is shown in Figure 4 to illustrate the 'hot spot' issue at the breast plate water passage. The conditions at the breast plate water passage for the original and inverted V designs are shown in Figure 5 and those for the Bateman design are shown in Figure 6. The data points represent the circumferential averages of the water passage wall heat flux and temperature at the location of maximum heat flux in each respective simulation. The data points are quantified in Table 1. The use of circumferential average data is consistent with the model of Marshall et al (2001) that was used to develop the Nukiyama boiling curves with which the data are compared.

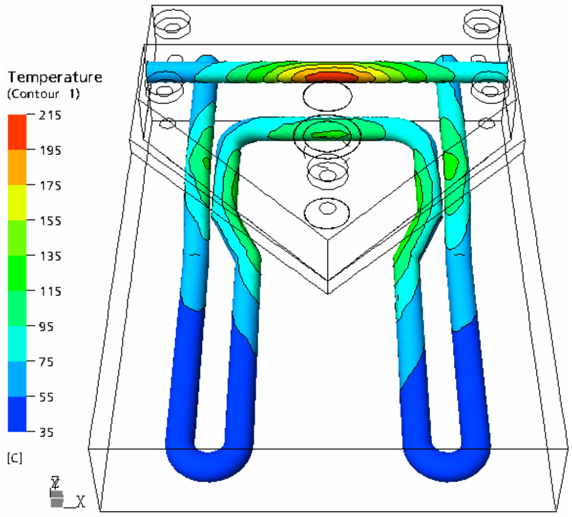

Figure 4: Contour Plot of Water Passage Wall Temperture in the Model for the Original Breast Plate Design Scenario.

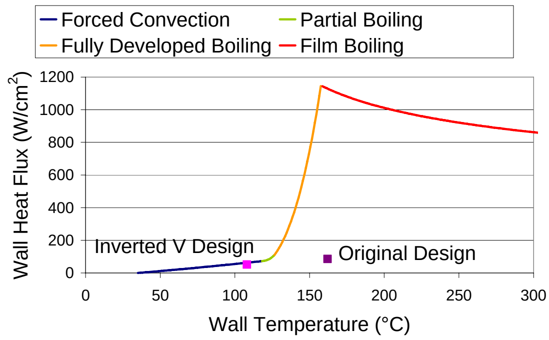

Figure 5: Nukiyama Boiling Curve 32mm diameter, 0.1MPa, 1.8m/s, 35°C supply

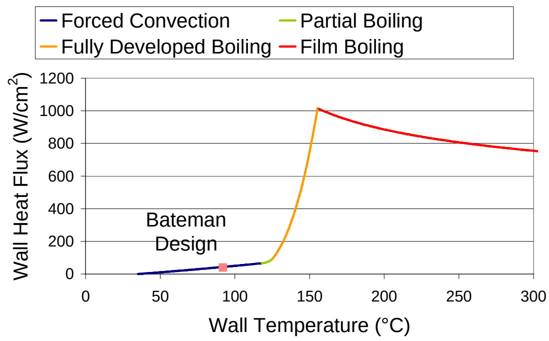

Figure 6: Nukiyama Boiling Curve for 50mm diameter, 0.1MPa, 1.8m/s, 35°C supply

Design	Circ. Ave. Wall Heat Flux (W/cm^2)	Circ. Ave. Wall Temperature (°C)
Original	86	162
Inverted V	52	108
Bateman	40	92

Table 1: Water Passage Wall data from CFD Simulations

DISCUSSION

Interpretation of Results

The CFD model did not account for boiling in the water passages. The CFD model always calculated the heat transfer at the copper-water interface according to forced convection heat transfer. This is why the point representing the original design on Figure 5 lies on the extrapolation of the forced convection region of the boiling curve for the corresponding conditions.

It cannot be inferred that film boiling would have occurred in the original design based on this analysis. However, it can be concluded that the heat transfer in the model was not consistent with forced convection, and therefore that the design did not meet the safety criteria.

The data point representing the inverted V design on Figure 5 lies on the region of the Nukiyama curve calculated using the forced convection correlation. However, the onset of boiling given by the Marshall et al (2001) model for the prescribed conditions in both the 32 mm and 50 mm diameter water passages was a wall heat flux 35 W/cm^2 and a wall temperature of 108°C. As the conditions in the inverted V design exceeded these conditions, boiling could not be ruled out in this design. The Bateman design was deemed safe because the conditions at the water passage did not exceed the criteria for the onset of boiling.

A photograph of the installed Bateman breast plate design immediately after plugging is shown in Figure 7.

Figure 7: Bateman Design Breast Plate Immediately after Plugging

Post Installation Model Validation

The installation and commissioning of the Bateman design presented the opportunity to validate the complete model. During the first month of operation with the Bateman breast plate, the measured bulk cooling water temperature rise across the breast plates ranged between 2°C and 3°C, which compared well with the model that calculated a bulk temperature rise of 2.0°C Bateman breast plate.

Because the temperature of the tapping channel surface in the simulations was lower than the slag solidus in all three simulations, a thin solidified layer existed at the tapping channel wall in the results as a consequence of the numerics. However, there was no significant solidified layer maintained in the tapping channel in any of the simulations. On occasion, a collar of solidified slag has been observed around the taphole on the cold face of the breast plates in practice. However, this has typically occurred at low slag temperatures.

ACKNOWLEDGEMENTS

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The Film-2000 free ware software was used to generate data for the curves shown in Figure 5 and Figure 6.

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