EVALUATING AC AND DC FURNACE WATER-COOLING SYSTEMS USING CFD ANALYSIS

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ABSTRACT

Fluid flow and heat transfer characteristics of various water-cooling systems were evaluated using the multi-physics capability of STAR-CCM+® Computational Fluid Dynamics (CFD) analysis as part of Bateman Engineering Projects ongoing equipment development program to design and manufacture robust pyrometallurgical process vessels capable of increasing campaign lives between partial and complete rebuilds.

The AC Furnace equipment development focussed on roof cooling panels which are simultaneously optimised for ease of manufacture and operational safety. In the case of vessels used in conjunction with DC open arc, open bath smelting, lower side wall refractory cooling systems capable of resisting chemically aggressive slag combined with erosion and high convective heat transfer from bath movement have been commercialised and refined, based on Composite Furnace Module (CFM) technology originally developed and patented by the University of Melbourne.

A two stage approach is generally adopted to accelerate the process of obtaining an understanding of the dominant parameters and mechanisms which are used in turn to limit design iterations and develop optimal solutions rapidly. The first stage involves the analysis of fluid flow and pressure drop characteristics of a particular configuration for early elimination of designs with unfavourable flow characteristics including excessive recirculation zones and stagnant areas. This is followed by conjugate heat transfer, in which the heat transfer characteristics of the system are derived directly from the fluid flow regimes. The results are used to eliminate designs which dissipate heat poorly, detected as areas with high surface temperatures or prone to reduction in film transfer coefficients by boiling.

This paper demonstrates the approach followed in more detail, and presents theoretical results of evolving equipment design performance.

1 INTRODUCTION

Turnaround time for a new design is of critical importance to get the best product to the market as soon as possible. Bateman Engineering Projects have used STAR-CCM+® over the past three years to evaluate different designs which has generally facilitated progress from inception to manufacturing within months. This modeling software has been employed for both AC- and DC Furnace water-cooling systems and two typical applications will be discussed in this article.

2 AC ARC FURNACE ROOF PANELS

Covered AC Furnace roofs are typically assembled from a few large, monolithic panels, bolted together along their common edges using an insulation detail to segregate the sub-assemblies electrically. The panels extend from the periphery of the roof to near the electrode PCD, and the assembly is closed by means of the so-called ‘delta section’. Each panel incorporates feed, inspection, off-gas and over-pressure control ports in different combinations as required. Symmetry is difficult to achieve due to layout constraints, making spares rationalisation and storage problematic. The large panels are difficult to remove and replace during maintenance shutdowns. The unavoidable triangular shape of the panels, together with discontinuities introduced by the feed ports pose many challenges to obtain a design that can be water cooled efficiently and is easy to fabricate. The resulting design is often a compromise. One of our original roof panel designs on the SA Chrome AC Ferrochrome Furnace in Rustenburg, South Africa was analysed using CFD to assess problem areas and initiate a design upgrade exercise.

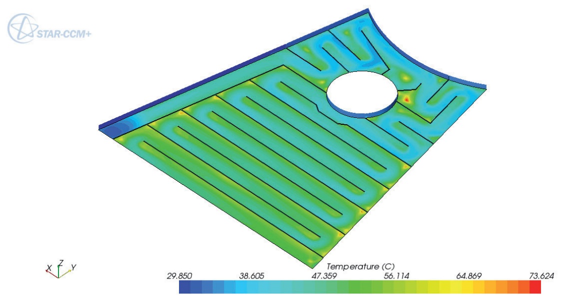


Figure 1: Surface temperature distribution in a typical monolithic AC furnace roof.

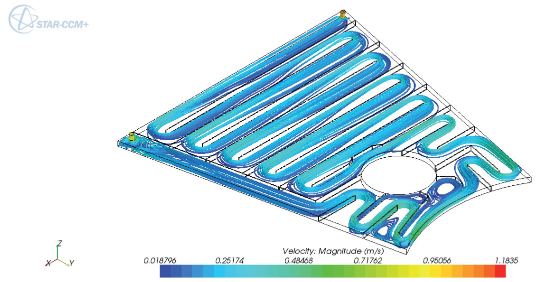


Figure 2: Velocity streamlines in the same roof panel.

The theoretical maximum surface temperature is acceptable provided that the panel is operated under conditions similar to the assumed boundary conditions. The internal rectangular, serpentine passages give rise to stagnant flow areas, particularly where the cooling channel pattern is interrupted at the feed port. Note the correlation between stagnation and localised hot spot formation.

The design criteria for the conceptual design work were to reduce or eliminate the internal passages, improve flow around circular discontinuities such as feed ports, and modularise the roof with smaller, symmetrical panels, which would be easier to replace in service. A preliminary generic model with representative geometry, heat load and flow rate parameters was evaluated using arrays of small vertically orientated cylindrical baffles to disperse and marshal the flow from a single inlet to a single outlet respectively without the need for serpentine passages. As an alternative, an array of 4 jets situated at the periphery of the panel was used to induce flow towards a single outlet at the inner edge without serpentine passages. The results were not convincing, but it was noted that the cylindrical baffles effectively distributed flow across the panel cross section. The resulting low velocity produced corresponding low heat transfer coefficients, which restricted heat transfer. The rectangular serpentine concept was then revisited and refined, using strategically positioned cylindrical baffles to improve flow in areas where flow stagnation occurred.

This culminated in the design of a modular furnace roof shown in Fig 3. The joint lines between the panels were arranged relative to the major port and duct positions to minimise the number of different shapes, which need to be designed, analysed and fabricated. Each module was analysed using the multi-physics capability of STAR-CCM+® and the results of three different panel types are presented below.

2.1 Water Cooled Panel Type Zero

This panel forms the inner edge of the electrode ports and incorporates provision for feed ports, which direct raw material towards the outer electrode surfaces of the electrode, thereby encouraging submerged arc operation without mechanical rabbling. The baffles are arranged to obtain a typical serpentine flow pattern through the panel, but the flow is directed around the feed port through a circular passage in place of the traditional dead-ended configuration. Cylindrical baffles are positioned in areas where the flow tends to stagnate or re-circulate at abrupt changes in direction, thereby promoting uniform flow. The hot face of the panel was fixed at a constant heat flux of 15 kW/m². All other external walls were adiabatic and the inlet water temperature and velocity was fixed at typical values for an AC furnace roof.

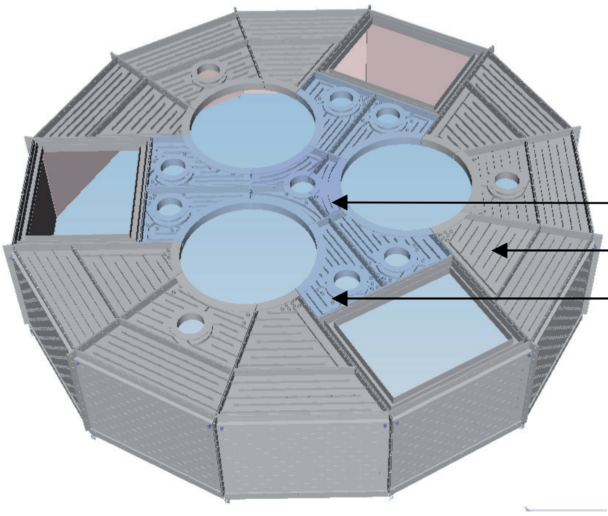


Figure 3: CAD model of the modular roof.

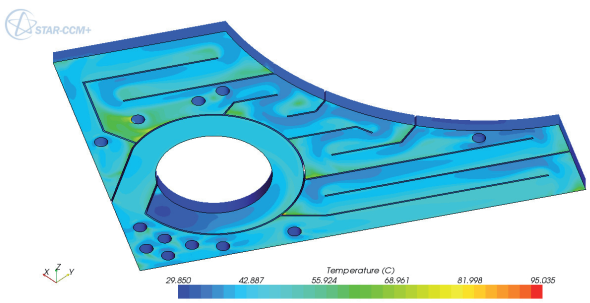


Figure 4: Surface temperature contour distribution on the Type Zero roof panel.

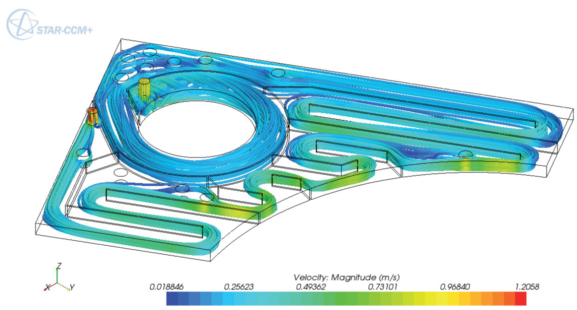
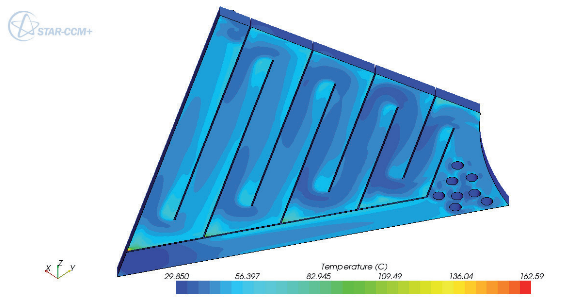


Figure 5: Streamline velocity contour distribution in the Type Zero roof panel passages.

The constant heat flux boundary condition is designed to identify stagnant flow areas, because these areas are characterised by higher thermal gradients to transfer the heat from the hot face to the cooling water. Hot spot formation in the final design is thereby predicted. This analysis and associated boundary conditions estimates a local maximum surface temperature of 95 °C in one of the sharp corners. Swirling is evident as the water changes direction at inlet and outlet pipes, enhancing heat transfer by turbulence as a forced convection heat transfer mechanism.

2.2 Water Cooling Panel Type Two

This panel is representative of the heat transfer and flow problems that have to be addressed in the design of peripheral panels. The inner edge of this panel forms the outer edge of the electrode port. Since the panel does not incorporate any feed ports, a traditional layout of the serpentine cooling passages was adopted. Preliminary CFD runs identified a large stagnant flow zone adjacent to the electrode port. This could have been reduced by grading the cross section of the passages from the outer to the inner edge of the panel, but this would have resulted in increased fabrication complexity. It was decided to assess the effect of cylindrical baffles in this area. Similar boundary conditions and water loading per square meter of hot face were applied as for the type zero panel.



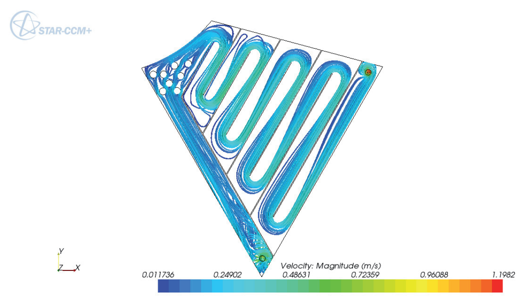


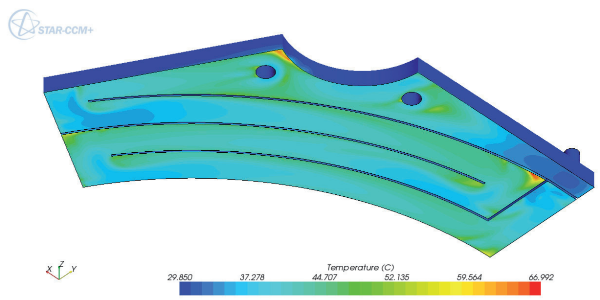
Figure 6: Surface temperature contour distribution on the Type Two roof panel.

Figure 7: Streamline velocity contour distribution in the Type Two roof panel passages.

The CFD analysis predicts hotspots in the recirculation zones of the serpentine passage corners adjacent to the supply passage. The highest estimated temperature is 165 ^{o}C at the start of the last outlet passage, which necessitated further design refinement (not presented). Swirling is evident as the water changes direction at the inlet and outlet pipes. Streamlines demonstrate generally uniform flow in the serpentine passages with some recirculation after changes in direction and wake creation downstream of the cylindrical baffles. The local hot spot was later addressed by investigating changes in the configuration of serpentine passages.

2.3 Water Cooling Panel Type Five

This panel is designed for the critical 'delta section' of the roof and incorporates the feed port which ensures that the area between the electrodes containing the superheated primary reaction zone remains covered with raw material. The panel is divided as shown to maintain electrical isolation between the electrodes. Water supply is designed to start and end at the outer edge of the delta for convenient connection to the cooling water reticulation system of the roof. Cylindrical baffles were installed in the converging-diverging portion of the water passages adjacent to the feed port to limit stagnation. Similar boundary conditions as those applied to the previous models were specified.



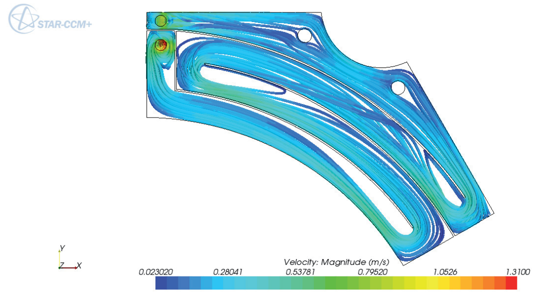


Figure 8: Surface temperature contour distribution on the Type Five roof panel.

Figure 9: Streamline velocity contour distribution in the Type Five roof panel passages.

The CFD analysis of the type five panel predicted a local maximum surface temperature of 67 °C. The flow patterns in the serpentine passages are similar to those in the previous models, providing designers with an intuitive, qualitative tool for anticipating the flow patterns in the balance of the panels that were designed for the modular roof.

3 COMPOSITE FURNACE MODULES (CFM) FOR FURNACES

3.1 Introduction

The technology of cooling furnace refractory lining material by means of water cooled copper panels in order to extend the lining life is well established. The copper panels and refractory are configured to increase the heat flux from the process to the water passages so that a freeze lining comprised of the furnace bath constituents forms on the hot face. The freeze lining which is inert to the process protects the refractory from both corrosion and erosion. The frozen layer is vulnerable to localised failure due to process disturbances and spontaneous spalling, but the sudden increase in the heat flux promotes its rapid re-establishment, minimising transient refractory damage. This facilitates a refractory lining system with potentially indefinite life. A specific configuration comprised of a copper base plate with integral pins covered by castable refractory was developed and patented by the University of Melbourne, and commercialised by Bateman who now hold a license for the technology. The novelty of this technology, termed Composite Furnace Modules (CFMs), is its ability to maintain a uniform hot face temperature, which limits thermal stress induced spalling of the freeze lining, and configurability to suit a wide range of design heat flux conditions.

The first commercial application was the lower side wall replacement of the electric arc slag cleaning furnace at Olympic Dam's BHP Billiton Operations in Australia[1], which is still in operation some six years later, in contrast to the former campaigns of 12 – 13 months. Similar success has also been obtained with the side wall and roof panels retro-fitted into a copper flash furnace at Kalgoorie[2]. CFM technology demonstrated the ability to resist the corrosive conditions associated with the smelting of nickel laterite ores in a large scale trial utilising the 1.8 MW DC arc test furnace at Mintek[3]. Bateman has subsequently been awarded a contract for the supply of a 12 MW DC demonstration smelter, which produces ferronickel from a laterite ore in Southern Russia.

3.2 Design Methodology

Whilst significant design and operational data were available to guide the designers of the furnace, the level of customisation required for this specific application required rapid prototyping techniques to optimise the design and complete the manufacture of the CFMs within the project schedule whilst ensuring that the cooling system performs adequately once in service. Copper pin to refractory area ratios for different zones needed to be confirmed, as well as cooling coil configuration to ensure adequate cooling whilst providing sufficient redundancy to facilitate uninterrupted operation in the event of partial cooling coil failure.

Previous experience during the laterite trials at Mintek had highlighted that the CFMs needed to be supported from refractory bricks just above the maximum design alloy bath depth to ensure that there was little or no contact between the alloy and the bottom support fingers of the copper coolers. This ensures that the lower areas of the panels are not thermally overloaded by molten alloy contact. However, the brick layers cannot be too deep or the bricks will not be adequately cooled resulting in under-cutting by the alternating mechanisms of slag corrosion and thermal contact shock as the slag-alloy interface oscillates during the production cycle. This influenced the boundary conditions specified to ensure conservative analytical results. The shop assembly of the main CFM side wall panels with openings for the installation of the alloy and slag tap hole inserts and tap blocks is shown in Fig 10. The design of each unique component was checked using conjugate heat transfer analysis.

3.3 Slag Taphole CFM Panel Insert

The CFM panels are all similar in size but two are customised to house the slag tap holes and two for the alloy tap holes. The slag tap hole is contained in a sub-panel or insert so that this high wear area of the furnace can be conveniently replaced without replacing the entire panel. Sufficient cooling must be provided to withstand running conditions, but not be overcooled to prevent easy taphole opening. The pin geometry needs to take into account the typical trumpet profile that forms as the taphole wears. The cooling passages need to be configured so that none are reticulated below the taphole and that they are positioned to avoid oxygen lance damage. These constraints were optimised using previous design experience and rapid prototyping techniques. The pin configuration was evaluated with new and worn castable refractory lining in place. A thermal slag process boundary condition and forced convection heat transfer coefficient was applied to the hot faces of the insert and internal cylindrical surface of the taphole (tap conditions). All other surfaces were assumed to be adiabatic.

Figure 10: Shop assembly of the 12 MW DC Furnace CFM side wall cooling panels.

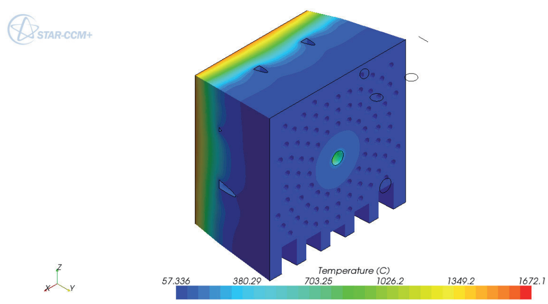


Figure 11: Surface isotherms of the slag tap hole CFM insert refractory lining – new condition. View from the cold face.

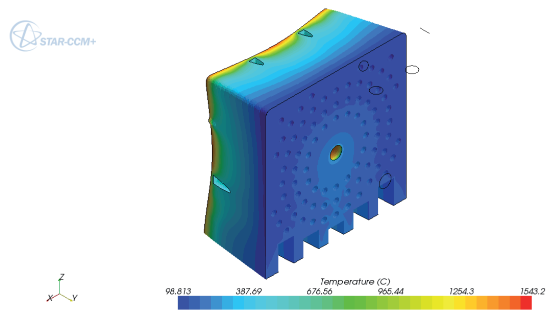


Figure 12: Surface isotherms of the slag tap hole CFM insert refractory lining – worn condition. View from the cold face.

The cooling passages in the copper base panel (not shown) are configured in an inverted ‘U’ shape similar to the alloy taphole discussed below to avoid the presence of water below the tap hole. No freeze lining thermal resistance was applied in both cases. The heat flux associated with the new lining could be dissipated without any isotherm distortion associated with the vertical asymmetry of the cooling pipes. The analysis of the worn lining was considered to be conservative because the modeled worn shape exposed greater copper pin surface area than expected in practice. The vertical asymmetry distortion of isotherms associated with the larger heat flux through the worn lining confirms the effect of the inverted ‘U’ pipe layout.

3.4 Alloy Taphole CFM Panel and Inserts

The design philosophy of the alloy taphole CFM panel is similar to that of the slag tap hole. However, whilst slag is tapped directly through the slag CFM panel, the alloy CFM insert houses a refractory composite taphole in the rectangular doghouse shown in Fig 14. Routine tap hole rebuilds are carried out without removing the insert, but if the insert is damaged, it can be replaced without disturbing the main panel to which it is attached. The alloy tap hole also contains an externally mounted water cooled tap block housing a cylindrical, tapered fused magnesia insert, shown as an outline in Fig 16. The tap block is exposed to the greatest wear from lancing and downward erosion from the alloy stream. It is designed for 1st stage maintenance of the taphole composite by total removal and replacement with a spare. If the copper is in satisfactory condition, the fused magnesia can be replaced, and the unit returned to service. Each component of the taphole assembly is optimised independently, although some pin configuration compromises were required at the interfaces. The cooling passage layouts in the alloy insert and tap block is an inverted 'U' (similar to the slag insert) for safety against alloy ingress in the event of a vertically downward burn through.

An approximate boundary condition with the required level of conservatism was applied to speed up the CFD analysis, which involved several runs during the development of the design. A fully worn lining was assumed with the tips of the copper pins exposed to the process. Under this condition, most of the heat conducted from the process to the water passages flows in the pins. The refractory between the pins and freeze lining were omitted, simulating the heat flux of a freeze lining failure over the entire panel and insert, rather than localised failure as observed in practice. A thermal slag process boundary condition and forced convection heat transfer coefficient was applied to the tips of the pins exposed to the slag. The analysis allowed for alloy contact with the lowest level of pins characterised by a thermal alloy process boundary condition and forced convection heat transfer coefficient. All other surfaces were modeled as adiabatic.

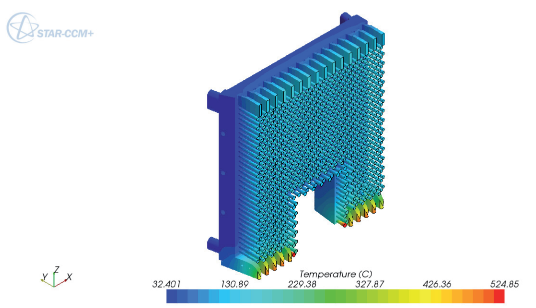


Figure 13: Surface temperature distribution of the DC Furnace CFM side wall panel containing the alloy tap hole (view from the hot face without refractory).

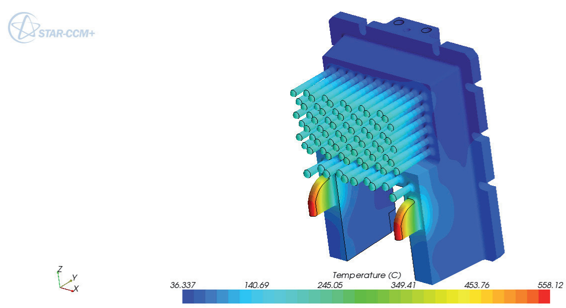
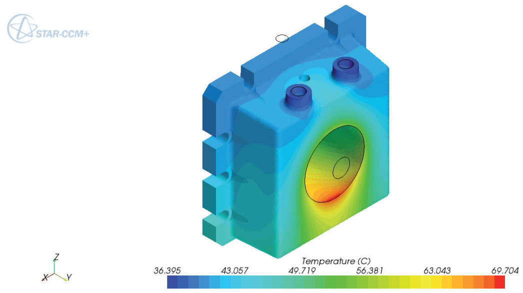


Figure 14: Surface temperature distribution of the DC Furnace CFM alloy tap hole insert panel (view from the hot face without refractory).

It was established that the water flow rate was inadequate during the initial runs carried out to optimise the cooling passage layout. This was detected by cooling water pipe internal surface temperatures exceeding 100 ^{o}C caused by low film coefficients corresponding to the low flow velocities. The problem was overcome by increasing the water flow rate and reconfiguring the external pipe circuits so that the design supply pressure of the cooling water reticulation system was not exceeded by a satisfactory safety factor.

The CFM alloy tap block was evaluated under simulated tapping conditions. A thermal alloy process boundary condition and forced convection heat transfer coefficient was applied to the inner surface of the fused magnesia insert. All other boundary surfaces were assumed to be adiabatic. The temperature dependent thermal conductivity of the insert was modeled using the datasheet information from the refractory supplier. This demonstrates the ability to handle additional non-linear phenomena within the conjugate heat transfer capabilities of STAR-CCM+®.



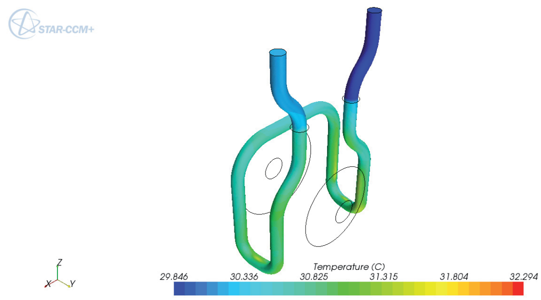


Figure 15: Surface temperature distribution of the DC Furnace alloy tap block.

Figure 16: Cooling passage surface temperature distribution in the alloy tap block.

The water flow rate was also found to be inadequate during the initial runs carried out to optimise the cooling passage layout. The layout was constrained by the need to avoid clashes with the external pipework, which is quite congested in this area due to the pipes supplying to the tap block.

4 CONCLUSIONS

A rapid prototyping methodology supported by CFD analysis to provide valuable guidelines for the design of the ‘next generation’ AC modular roofs has been demonstrated. The existing design was analysed to assess areas for improvement. Generic models were then used to analyse the effects of different cooling water distribution systems within the roof panels. Cylindrical baffles were shown to be effective at dispersing flow across the panel cross section between the inlet and outlet without serpentine passages but the average water velocity was too low to develop satisfactory heat transfer film coefficients. A cooling scheme incorporating submerged jets at the panel periphery failed to generate sufficient turbulence for adequate heat transfer at typical cooling system supply pressures. The baffle concept was then incorporated into conventional serpentine cooling systems with rectangular cross sectional areas to maintain the flow velocity and uniform distribution at discontinuities, which could not be practically avoided. This culminated in the optimisation of the overall and internal cooling passage layout of the modular roof.

The CAD modeling of the CFMs for a 12 MW DC FeNi smelter was iteratively carried out in conjunction with CFD analysis. This ensured that solutions to physical layout problems with the copper base plates, cast in monel cooling water passages and pin configuration to obtain a design suitable for manufacture simultaneously corresponded to a design with the required heat dissipation characteristics. Direct exchanges of compatible solid model entities between CAD and STAR-CCM+® facilitated analysis without the need to repair or modify the models after importation into the CFD analysis application. This rapid prototyping approach assisted in maintaining the project schedule whilst the accuracy of the simulations and conservative boundary conditions ensure that the designs will perform adequately in service.

5 REFERENCES

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