SOME CONSIDERATIONS FOR SAFER FURNACE COOLING

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ABSTRACT

Modern furnace designs often incorporate extensive use of cooled elements to achieve long campaign lives at high operating intensities. However, contact between water and high temperature fluids can result in powerful Boiling Liquid Expanding Vapour Explosions (BLEVEs). Therefore cooling such elements with water carries inherent risks when used under slag and particularly below molten metal or matte. Alternative cooling media exist that can reduce or eliminate the risk of BLEVEs. These media are analysed and discussed in the context of deeply cooled furnace elements. Important factors in selecting alternative coolants are explored including: critical heat flux, thermal limits, toxicity, flammability, unit cost, etc. Key cooling system design criteria are reviewed in the context of both traditional and alternative coolants. Results of Computational Fluid Dynamics are presented for an example tap-block cooler design using a number of selected coolants. Research needs to advance the safe use of alternative coolants are presented.

KEYWORDS
Coolant, cooler, furnace, safety, tap-block

INTRODUCTION

Many modern furnace designs including those for: (i) electric steel making, (ii) iron blast furnaces, (iii) non-ferrous sulphide smelters, (iv) slag cleaning and (v) fuming, utilize coolers of either steel or copper construction in order to either stabilize refractory or create a so-called 'freeze lining' of slag. Normally such coolers utilize water, although a few installations have used synthetic oils (Kennedy, Nos, Bratt, & Weaver, 2013). Coolers have been highly effective in prolonging refractory life and thereby lengthening furnace campaigns. As a result, some designs such as for Electric Arc Furnace (EAF) steelmaking now use cooled structures to build nearly complete walls and roofs.

Copper is a commonly used material in modern cooler designs, due to its excellent heat transfer properties, relatively low cost, and ease of fabrication. A typical composite wall construction of refractory and copper coolers using cast-in pipes is illustrated in Figure 1 (MacRae, 2010). Such a design sometimes involves the use of a vertical binding system to ensure adequate cooler to refractory contact where necessary. Figure 1 demonstrates the use of deep water cooling, which can operate at or below the metal level.
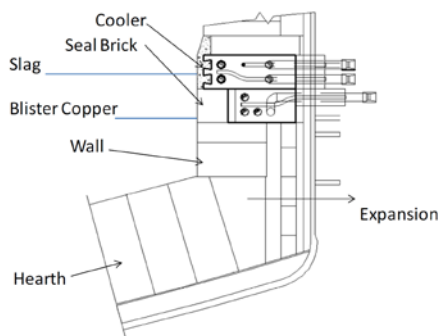

Figure 1 – Composite furnace wall using cast copper coolers (MacRae, 2010)

Fatal incidents due to steam explosions are reported at an approximately annual frequency in the metallurgical industry. Actual frequency is likely much greater as there is no industry wide systematic procedure for the collection, analysis and distribution of such information (Oterdoom, 2014a). The magnitude of the potential risks associated with deep water cooling (as shown in Figure 1) are therefore substantial if not perfectly quantifiable. Coolers can experience a number of situations which may initiate a hazardous water leak (Kennedy et al., 2013):

1. Contact with molten material and particularly matte or metal directly on the cooler hot-face (often due to loss of hot-face protective refractory),
2. Transition from natural convection to forced convection heat transfer at the hot-face,
3. Corrosion of the material of construction (e.g., due to labile sulphur or acid attack),
4. Damage due to thermal stresses producing cracks in the casting or welded-in plugs (for drilled and plugged designs),
5. Mechanical/thermal damage due to tapping operations (in the case of a cooled tap-block),
6. Damage due to conduction of electric current (steel panels are particularly susceptible), and
7. Loss or reduction of coolant flow.

Direct contact between high thermal conductivity matte or molten metal and a cooler is one of the most serious 'acute' scenarios that can lead to a leak in minutes and subsequently an explosion if water cooling has been used. The application of intensive water cooling to tap-holes therefore carries special risks as it puts water and molten metal together in a forced convection environment, and directly at the point 'where the man meets the metal'. The possibility to use a coolant less prone to explosions than water in this critical application is the main focus of this paper. This paper will explore the application of alternate coolants to a copper tap-block design incorporating cast-in pipes of cupro-nickel (MacRae, 2001). Coolers utilizing cast-in pipes are relatively common as these can be produced with virtually any geometry.

BOILING LIQUID EXPANDING VAPOUR EXPLOSIONS (BLEVEs)

Mixing water and liquid metal or matte can result a rapid build-up of gas pressure due to vapour evolution. If water is released under liquid metal or matte (or the reverse), BLEVEs can be expected (Abbasi & Abbasi, 2007) if a triggering event occurs. For some metals (like lead or tin) a BLEVE can occur even in the absence of an external trigger (Hildal, 2002). Peak pressure and blast wave propagation velocity for metallurgical BLEVEs can be substantial and definitely in the range for explosions and not 'deflagrations', as indicated in Figure 2 for molten metal falling into liquid water (Rizk, 1990). Blasts can be very powerful as indicated by Table 1. Hot furnace contents can be ejected from the vessels (Tveit et al., 2006), and windows, walls and roofs can be destroyed at great distances as indicated in Table 2.
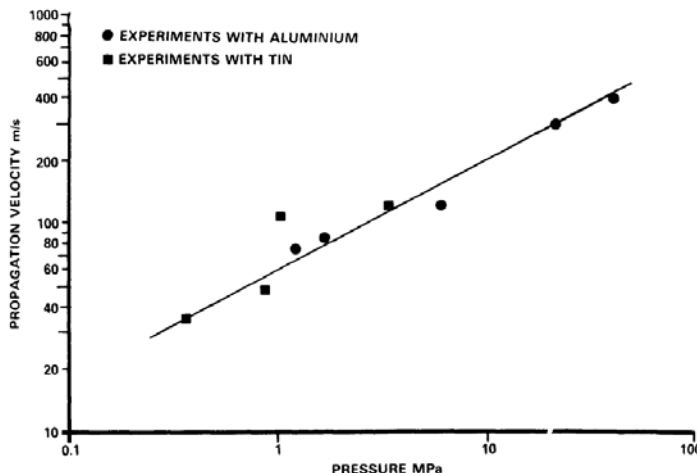

Figure 2 – Blast wave propagation velocity vs. peak blast pressure for liquid metal dropped into water
(Rizk, 1990)

The mechanisms of water-metal explosions are complex and beyond the scope of this paper; however, they are believed to involve a rapid and thorough dispersion of the phases, which dramatically increases interfacial area and the total rate of heat transfer (Hildal, 2002). A self-propagating shock wave appears to be possible, which results in the high pressures and velocities indicated in Figure 2. While some argue that hydrogen plays a key role in the size of explosions, available data would suggest otherwise (Hildal, 2002; Rizk, 1990). Hydrogen may lead to large secondary chemical explosions if mixtures with oxygen are created (Shick & Grace, 1982), as was apparently the case with the recent Fukushima reactor failures.

Table 1 – TNT equivalent of explosion resulting from the specified mass of water interacting with 1000 kg of a given molten metal (Babaitsev & Kuznetsov, 2001)

Metal	TNT equivalent of specified mass of water				
	1 kg	5 kg	10 kg	50 kg	100 kg
Steel 12Kh18N9T	0.82	4	7.8	33	57
Aluminum	3.17	15.9	32	176	200

Table 2 – Effects due to 26 kg of water interacting with 1000 kg of liquid aluminum
(Babaitsev & Kuznetsov, 2001)

After-effects of explosion	Distance, m	Pressure, kPa
Breakage of glass	250	2
Collapse of roof	41	14
Destruction of interior walls	23	28

CONSIDERATIONS FOR SAFE DESIGN AND OPERATION OF COOLING SYSTEMS

Boundary Conditions and Thermal Loads – Steady State and Dynamic

Typical copper cooler operating heat fluxes are of the order of 20-80 kW/m^2 for slag and often over 100 kW/m^2 in metal or matte zones (Degel, Kempken, Kunze, & König, 2007; Nelson et al., 2004; Stober et al., 2007; Van Manen, 2009). During tapping operations tap-hole coolers experience dynamic changes in heat fluxes to values that can be in excess of 300 kW/m^2 (Nelson & Hundermark, 2014).

Slag coolers

Slag coolers in well-designed furnaces operate with a nominal natural convection heat flux boundary condition, with the flux determined by the slag superheat prevalent at the wall (Joubert, 2000; Kang, 1992). Assuming a typical silicate slag natural convection heat transfer coefficient of 425 W/m^2·K (Kennedy et al., 2013), a heat flux of 64 kW/m^2 would be expected for 150 K of slag superheat.

In order to maintain a stable freeze lining of slag, all energy arriving at the wall must be removed (Merry, Sarvinis, & Voermann, 2000; Verscheure, Kyllo, Filzwieser, Blanpain, & Wollants, 2006). If coolers are installed with an initial refractory lining, then a thermal boundary condition might prevail until sufficient refractory has been consumed that a minimal freeze lining is formed. At this point the residual refractory will in theory be protected from chemical attack over the long term. The thermal conductivity of the refractory and the total heat flux will determine the equilibrium thickness and this should be of the order of 50 mm to maintain long term thermal/mechanical stability. High thermal conductivity refractory should be considered in order to ensure a thick residual lining for the nominal steady state heat flux. A thicker residual lining will always represent a safer thermal barrier (e.g., a greater thermal mass) in the event of a dynamic incident such as transition to forced convection at the wall, which can result in an order of magnitude change in heat flux, i.e. to values of several hundred kW/m^2.

Metal and Matte Coolers

Coolers with partial or total coverage by matte or metal require refractory protection in order to reduce nominal heat fluxes to tolerable limits (as shown previously in Figure 1). With this temperature boundary condition, the nominal heat flux in the metal region will be determined primarily by the metal temperature, the refractory thickness and thermal conductivity. Assuming a 5 cm residual refractory thickness, a thermal conductivity of 4 W/m·K typical of high MgO chrome-magnesite refractory (Donaldson, Ham, Francki, & Schofield, 1992) and a thermal driving force of 1300 K, would result in a heat flux of 104 kW/m^2.

A loss of refractory represents a critical thermal emergency for a metal or matte cooler as it would transition to a heat flux boundary condition in a region of 'excellent' heat transfer. This is a significant risk in the so-called 'tidal' zone. Tidal zone coolers see alternately slag and metal due to changes in level as a result of batch metal tapping. This issue can be particularly acute if the metal operating temperature is greater than the slag liquidus. In this case, coolers are unable to generate a stable slag freeze lining and refractory erosion can be expected to be rapid. Slag will dissolve refractory until a freeze lining of slag is achieved and hot metal will re-melt frozen slag ensuring rapid and continuing refractory erosion. Cooler heat fluxes will therefore increase steadily over the course of such a furnace campaign, which will in all likelihood be of very short duration. Slag 'engineering' (Campforts, Blanpain, & Wollants, 2009) might be applied to avoid this situation by raising the slag liquidus over the metal operating temperature, thus ensuring a stable freeze lining in the tidal zone. This should also allow furnace operation with lower slag superheat for a given metal liquidus. Furnace operability is greatly improved if the slag liquidus is equal to or slightly higher than metal liquidus (e.g., 0-50 ºC), while the reverse situation tends to result in either high slag superheat (and cooler heat fluxes) or low metal superheat (and potential tapping issues).

Tap-hole Coolers

Tap-holes are special slag or metal/matte coolers which experience forced convection heat transfer: (i) during tapping as a result of bulk liquid flow, and (ii) during plugging due to vapour evolution from the clay and the resulting gas stirring inside of the furnace. Thermal design of tap-holes must allow for forced convective heat fluxes of several hundred kW/m^2 during tapping operations and therefore have one of the lowest safety factors when considering the relation between peak 'nominal' and burn-out heat fluxes.

Tap-holes (metal and matte in particular) are difficult to model with precision due to the high dynamic variations in heat flux and the impact of operator actions (e.g., drilling and lancing). Large variations in dynamic heat fluxes increase the risk to personnel and it is not surprising that the engineering industry has focused extensively on systems to improve tap-hole operational safety (Gunnewiek, Suer, MacRosty, Gerritsen, & Karges, 2008; Plikas, Gunnewiek, Gerritsen, Brothers, & Karges, 2005; Sadri, Gebski, & George-Kennedy, 2008; Tracy, MacRosty, Zhao, Gunnewiek, & Gerritsen, 2007).

Rather than depending only on engineering design and extensive monitoring, inherent risk reduction by the replacement of water with alternative coolants having less or no potential to generate a BLEVE would seem a reasonable approach to improve furnace safety, and particularly for small high risk zones like metal and matte tap-holes.

Thermal Emergencies, Required Safety Factors and Principles for Safer Designs

During high heat flux incidents natural convection boundary conditions are often replaced by forced convection, dramatically enhancing heat flux to coolers. This may be due for example to silicon/carbon 'reversion' reactions, as have been reported in the literature (Nelson et al., 2004). These reactions are caused by feeding of over oxidized material to an overly reduced furnace and rapid re-equilibration between metal and slag generating gas and stirring particularly at the slag-metal interface, i.e. below typical slag cooler elevations.

In order to protect coolers against dynamic heat flux events, it is necessary to design them with large safety factors. Safety factors should be based on the analysis of past data when available, considering the mean and standard deviations in the observed heat fluxes. Where benchmark operating information is available the cooler design heat flux should be equal to the mean hourly value plus >4.5σ in order to achieve a satisfactory Safety Integrity Level rating for continuous operation, for example one failure in the design life of the plant ("Application of IEC 61508 and IEC 61511 in the Norwegian Petroleum Industry," 2004). Where benchmark information is not available a starting point could be a cooler design flux 4 times the expected hourly average and a cooling system designed for two times the nominal total heat removal (Stober et al., 2007) or 100% of furnace power, whichever is smaller.

In a critical thermal event the enhancement of heat transfer due to nucleate boiling improves the heat transfer ability of the cooler and therefore nucleate boiling (i.e., below the Critical Heat Flux; CHF) can be considered as a 'safety' factor for so-called '2-phase' fluids like water or Mono-Ethylene-Glycol (MEG). Single phase fluids such as silicone oils or Pb-Bi will not benefit from this effect. Many organic based single phase fluids will crack potentially forming damaging carbon deposits under such situations, which can further reduce heat transfer or result in a system blockage. Therefore organic fluids which boil are in general to be preferred over those that will crack at a given temperature.

Physical contact with liquid metal or matte on too great an area will produce heat fluxes at the cooling channels greater than the CHF, resulting in a transition to film boiling and eventually to 'burn-out' of the entire cooler. CHF is typically of the order of several MW/m^2, for low pressure forced convection cooling with water, at typical velocities between 1 and 3 m/s. The relationship between internal cooled area and external heat transfer area will define the relation between CHF and cooler burn-out heat flux. A reasonable first pass approximation can be made assuming that only the half-area of the cooling channels

facing the hot-face are effective at removing heat. 3D Finite Element Modelling (FEM) and Computational Fluid Dynamics (CFD) are required to obtain more accurate estimates.

Data and equations describing tube burn-out/CHF are available as functions of fluid velocity and undercooling (Bergles & Rohsenow, 1962; Chang & Baek, 2003). While the CHF can be estimated by a number of means, safe design practice typically attempts to create heat transfer conditions (e.g., large internal cooled area and high coolant velocity) that avoid the boiling regime and are therefore are far from the CHF. The heat flux for both incipient boiling and CHF are known to increase with the temperature difference between vapour saturation and the bulk, total pressure, and fluid velocity (Bergles & Rohsenow, 1962). So system safety can be enhanced by operating under positive pressure, at relatively low inlet coolant temperature and high velocities (at the cost of higher pumping energy).

Safety Systems

At present it is not possible to design a furnace cooler that will survive all potential situations, e.g. direct contact with highly superheated liquid metal or matte over their entire surface. A furnace integrity system is required to continuously monitor the furnace for dangerously high heat flux deviations in order to provide operators with sufficient warning time to render the furnace safe or evacuate.

Extensive furnace monitoring (e.g., heat fluxes, cooler temperatures, refractory and shell temperatures, etc.) using advanced instrumentation and integration of results into a so-called 'furnace integrity' system are considered mandatory for safe operation of modern furnaces using cooled structures (De Kievit, Ganguly, Dennis, & Pieters, 2004; Hopf & Rossouw, 2006; Joubert, Benade, Burmeister, & Meyer, 2007; MacRosty, Nitschke, Gerritsen, & Crowe, 2007; Oterdoom, 2014b). An adequate exploration of this topic is however, beyond the possible scope of this paper.

Redundancy

Given the potential consequences of cooler failures, a focus on safety in both design and operation is mandatory. Deep coolers should be built using redundant cooling circuits such that a minor leak or a loss of coolant flow in one circuit does not result in catastrophic failure. Each circuit should be capable of supplying sufficient cooling to handle the nominal heat flux including a safety factor. In this case a loss of coolant on one circuit will simply result in a safe furnace shut down. Cooling circuits cannot be placed in the 'shadow' of each other as this will result in a potential burn-out if the outer circuit fails, while the shadowed circuit will provide negligible cooling when both are in operation, thus greatly reducing the peak thermal load that can be accommodated in an emergency.

Single points of failure in a cooling system design should be avoided where possible. The ultimate embodiment of a two circuit mentality would incorporate redundant cooling plants for A and B circuits (Engvoll, 2007). Multiple redundancy single systems are typically used for furnace cooling. For example to maintain coolant supply and flow, it is not uncommon to use: electric pumps, backup pumps, diesel pumps, diesel electric generators, gravity head tanks, city water, etc. Yet many single points of failure typically remain that could result in a total loss-of-furnace, e.g.: piping manifold, PLC/control system, Motor Control Centre (MCC) and heat exchanger. Systems can be made both simpler and more reliable by a focus on complete independent redundancy. This should include the installation of Safety Instrumented Systems (SIS) separate from the plant control system in a manner similar to that now used for safety critical off-shore oil applications in accordance with IEC standards 61508 and 61511. The metallurgical industry could benefit from the strict application of these standards to high risk systems. Significant parallels exist with the off-shore industry from which practical guidance can be obtained to minimize the cost of implementation of advanced SISs ("Application of IEC 61508 and IEC 61511 in the Norwegian Petroleum Industry," 2004; Hauge, Hokstad, & Onshus, 2001).

System design issues will be discussed further in the context of additional requirements for non-water cooled installations.

COOLING SYSTEM DESIGN CRITERIA FOR 'ALTERNATIVE' COOLANTS

Alternative coolants represent special engineering challenges that may not be comprehended fully by those who have never designed or operated such a system. The first challenge is related to the fact that limited quantities of coolant will be available unlike when using water. Due to the cost, alternative coolants will never be present in unlimited quantities. The potential consequences of an ordinary leak will therefore be magnified many times.

As a critical SIL rated system, the cooling circuit piping must be built and inspected to a suitable standard such as Norsok Piping standard M-601, which is used in the Norwegian off-shore industry ("Norsok Standard M-601 Edition 5 Welding and Inspection of Piping," 2008). Non-critical equipment (e.g., electrical equipment) must not be cooled by the main furnace cooling system to minimize the points of failure in the piping system. Flanges should be minimized to reduce points of potential leakage ("Norsok Standard Technical Safety S-001, Rev 3", 2008). A flange 'management' system must be put in place to ensure that after maintenance every flange is equipped with its proper engineered gasket (note the high operating temperatures of some of these coolants), correct and accurately torqued bolts (after thermal expansion), and so on. Such a system should number and label each flange, and require an individual sign-off to establish that it is ready to return to service. Systems like pipe-in-pipe become 'discussable' for higher priced coolants. Coolant recovery systems should be considered, for example from the containment under the cooling plant and perhaps under major headers.

Heat exchangers must be on the high pressure side of the pumps due to the generally higher viscosities of alternative coolants in order to avoid the requirement for too much net positive suction head, and avoid the risk of pump cavitation or boiling in the heat exchanger due to reduced pressure. The system pressures must be designed such that oil leaks into water and not water into oil, or steam explosions may be experienced in the heat exchanger in the event of a tube failure.

Significant volumes (e.g., 2 or more system volumes) of coolant should be located in an upper drop tank. Coolant in the 'warehouse' will not be available in a critical emergency. Normal system refill can be automated based on continuous measurement of total system coolant volume. The refill system should be equipped with an alarm as these coolants operate in sealed and often pressurized systems, and do not experience significant vapour losses. Any refill logic must be able to distinguish a normal refill situation from that of a major leak. Coolant must not be added into a system with a major leak, as available coolant inventory is limited. It is preferable to stop coolant circulation in this circumstance (to preserve volume) and depend on a fully redundant cooling system, i.e. a Plant A and Plant B design. A fully redundant design ensures that at least a double failure is necessary to completely lose furnace cooling and experience a loss-of-furnace incident.

A lower 'drop tank' is required to accumulate system coolant during any maintenance or pressure relief scenario and allow it to be safely returned to the system. The value and availability of coolant in these systems is a major design consideration.

Pressure relief must be provided for in all furnace cooling systems including those using water. Often such devices are erroneously placed on headers. In a system utilizing a 2-phase fluid internal explosive events are possible within the cooling blocks themselves (for example if coolant flow is interrupted and re-established after a short time). A remotely located relief valve will result in the flexible hoses located at the outlet side of the cooler blowing off before such a pressure wave can travel down the piping system. Any pressure relief must be placed on the outlet side of the cooling block (where the pressure wave is experienced) and piped to a recovery tank to prevent loss of coolant.

Flow meters should be installed on the outlet loops of each cooling circuit to ensure that adequate flow is present at all times. Flow meters are not required on the inlet lines as loss-of-coolant detection by differential flow is typically not sufficiently accurate nor required for such an installation. Monitoring the total circulating volume can more precisely detect a loss-of-coolant, as described previously.

Instrumentation suitable for the maximum operating temperature (potentially up to 600 ºC for Pb-Bi) must be utilized. This may result in orifice plates or venturi meters being used over more modern devices with a lower thermal tolerance (e.g., coriolis mass flow meters or vortex shedders).

Provision should be made for coolant heating to a suitable viscosity for start-up depending on the low temperature viscosity of the coolant and the location of the system. In some cases it may be possible to circulate the fluid and allow it to heat due to friction. Obviously in the special case of a fluid like Pb-Bi, the system must be maintained continuously over the eutectic temperature of 123.5 ºC.

When flammable oils are used, suitable firewalls must separate backup equipment from primary equipment, pumping skids are best located outside of main buildings, and automated fire detection and suppression systems using foam or gaseous suppressants should be utilized. Gaseous suppression using Ar/N_2 and CO_2 can be used to reduce oxygen sufficiently low to extinguish fires, while maintaining a sufficiently high oxygen level to ensure personnel safety during egress.

Alternative Coolant's Heat Transfer Properties

Water cooling is so common that systems can be designed based on previous benchmarks or design standards such as: 1 m/s water velocity for 'normal', 2 m/s for 'moderate' and 3 m/s water for 'heavy' and recently 4 m/s for 'extreme' cooling service such as at a tap-hole. However, alternative coolants such as MEG, ISIS-B or Pb-Bi must be analysed for example using Nusselt number correlations to determine the required velocity to achieve an adequate forced convection heat transfer coefficient. Comparison with water by using the same correlations can then provide benchmark information for different classes of service.

The Colburn equation (Colburn, 1933) can be applied using bulk coolant properties to obtain conservative estimates of the heat transfer coefficients for water and organic coolants:

$$Nu = 0.023\, Re^{0.8}\, Pr^{1/3} \tag{1}$$

where:

$$Nu = \frac{hD_h}{k} \tag{2}$$

$$D_h = 4\frac{Channel\ area}{Channel\ perimeter} \tag{3}$$

$$Re = \frac{\rho v D_h}{\mu} \tag{4}$$

$$Pr = \frac{C_p \mu}{k} \tag{5}$$

and h is the average turbulent forced convection heat transfer coefficient between the channel wall and the bulk coolant [W/m^2·K], D_h is the hydraulic diameter of the channel [m], k is the average thermal conductivity of the coolant [W/m·K], C_p is the mean heat capacity of the coolant [J/kg·K], ρ is the average bulk coolant density [kg/m^3], and v is the average velocity in the cooling channel [m/s].

The Colburn equation (1) cannot be applied accurately to liquid metals where the Prandtl numbers are too low and lie outside of the range of the equation's validity. It is therefore necessary to use correlations developed for liquid metals (Notter & Sleicher, 1972):

$$Nu = 4.8 + 0.0156\left(Pe\right)^{0.85} Pr^{0.08} = 4.8 + 0.0156\, Re^{0.85}\, Pr^{0.93} \tag{6}$$

Applying Equations (1-6) it is possible to compare the performance of different coolants at various temperatures, as shown in Table 3 for 2 m/s and assuming a cooling channel consisting of a 1 ¼ " schedule 40 cast-in pipe. Representative data were selected for MEG ("Ethylene Glycol Product Guide,"

2013), ISIS-B ionic coolant (Filzwieser, Konetschnik, & Dreyer, 2014; Konetschnik, Filzwieser, & Filzwieser, 2013), and Pb-Bi (Martynov, Gulevich, Orlov, & Gulevsky, 2004).

A simple examination of Table 3 indicates that Pb-Bi is the best coolant under non-boiling conditions, and that water is second best. While MEG and ISIS-B have significantly lower heat transfer coefficients than water, given their larger range of operating temperatures this is not necessarily a major issue and requires further CFD analysis to examine the impact on copper operating temperatures. It can be shown using Equations (1-5) that ISIS-B would require a velocity of 6 m/s to achieve the same heat transfer results as MEG at 2 m/s.

Table 3 – Typical heat transfer related properties of some selected coolants

Cooling fluid	Approximate Range of Operation Min/Max ^oC	Temp for Ref. Data, ^oC	Density, kg/m^3	Heat Capacity, $J/kg \cdot K$	Thermal Conductivity, $W/m \cdot K$	Viscosity, $mPa \cdot s$	Prandtl Number	Reynolds Number at 2 m/s	Nusselt Number at 2 m/s	35 mm ID Pipe Forced Convection Heat Transfer Coefficient, $W/m^2 \cdot K$
Water	0/100	40	992	4174	0.634	0.6	4.3	1.1E+05	394	7130
MEG	-13/240	60	1087	2576	0.258	5.2	52	1.5E+04	185	1364
ISIS-B	50/200	60	1250	1600	0.128	13.0	163	6.7E+03	145	530
44.5%Pb-55.5%Bi	200/600	123.5	10150	146	14.2	1.4	0.015	5.0E+05	26	10625
Galden HT 200	-85/300	60	1715	1080	0.063	2.1	36	5.7E+04	488	872

Coolants can also be compared using many additional criteria besides simple heat transfer performance as indicated in Table 4. Galden HT 200 was reported on in a previous study (Kennedy et al., 2013) and is included in Tables 3 and 4 due to its non-flammability (a rare property for non-water based coolants) and previous use by Elkem and Alcoa in pilot furnaces of up to about 1 MW in scale.

Table 4 – Qualitative comparison of different cooling media

Coolant	Coolant Cost	Explosivity in Contact with Liquid Metal	Pumping Energy	Copper Operating Temperature	Flammability	Toxicity Excluding Ingestion	Burn Out Heat Flux	Comments
Water	Neg.	High	Low	Low	Non	Non	High	
MEG	Low	Neg.	Low	Medium	Low	Low	Medium	Limited explosion testing.
ISIS-B	High	Non	High	High	Non	Non	Medium	BHF assumes selection of higher velocity, e.g. 4 m/s.
Pb-Bi	Low	Non	High	High	Non	Low	High	Proven reactor cooling technology.
Galden HT 200	High	Neg.	Low	Medium	Non	Non	Low	Toxicity excludes decomposition products.

CFD MODELLING

CFD analyses have been performed for Water, MEG, ISIS-B and Pb-Bi in order to demonstrate the performance of non-water based 'alternative' coolants in a highly demanding application, i.e. at a tap-hole. Conditions similar to those in Table 3 were selected, i.e. a standard coolant velocity of 2 m/s, 1 ¼" schedule 40 pipe, and an applied base-case heat flux of 250 kW/m^2. Material properties for all fluids and solids were varied with temperature, where such information was available.

The computer program ANSYS CFX® was employed for the CFD analyses. Three dimensional (3D) models were developed using Solid Edge®. The model consisted of a rectangular block of 1 m by 1 m, with a simple pocket pattern on the hot-face as shown in Figure 3. Rounded edges were not included in the model for simplicity. The hot-face pockets were filled and an additional 50 mm layer of castable, with k=1.5 W/m·K was placed in front of the cooler. A uniform heat flux boundary condition was applied to the surface of the castable, which was subsequently varied from 50-500 kW/m^2 for each coolant. The cooling block had 2 intertwined cooling circuits to provide redundancy as discussed previously. Inflation layers were employed in the cooling medium at the interfaces with the cast-in pipes.

High conductivity copper (85% IACS, equivalent to low residual phosphorus deoxidized copper) was used in the simulation. The pipe coils were modelled with cupro-nickel (MacRae, 2001), for

maximum heat transfer, while also obtaining a metallurgical bond at the interface with the cast around copper and minimizing thermally induced stresses. A simple cylindrical graphite block was included for a tap-hole.
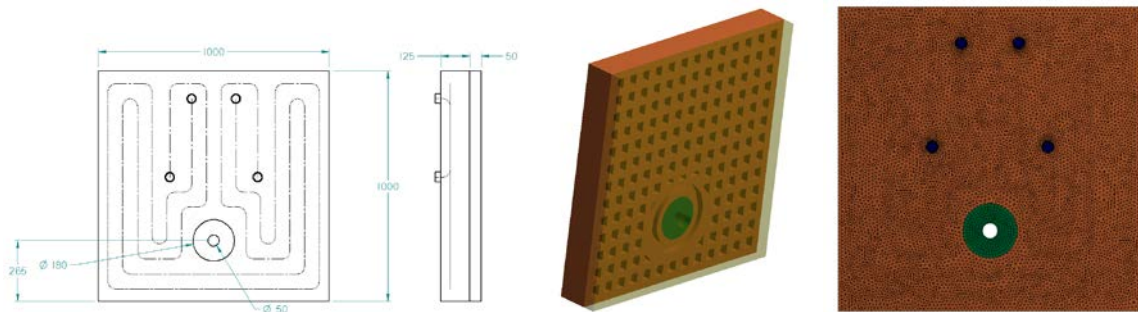

Figure 3 – Dimensions and images of the modelled tap-block incorporating dual cast-in cooling channels and a graphite lined tap-hole.

Isotherms have been plotted on the same temperature scale for ease of comparison as shown in Figure 4 for the base-case scenario. A practical maximum copper temperature of 450 ºC was used for the isotherms, as above this temperature the copper can oxidize rapidly (Aniekwe & Utigard, 1999). Peak copper temperatures increased from water to MEG, PbBi and then to the ionic fluid ISIS-B. While the copper temperature for ISIS-B at 2 m/s was unacceptably high from an oxidation perspective, this could easily be rectified by increasing the coolant velocity to 4 m/s, which resulted in both an acceptable maximum copper temperature of 433 ºC, as well as acceptable coolant temperatures.
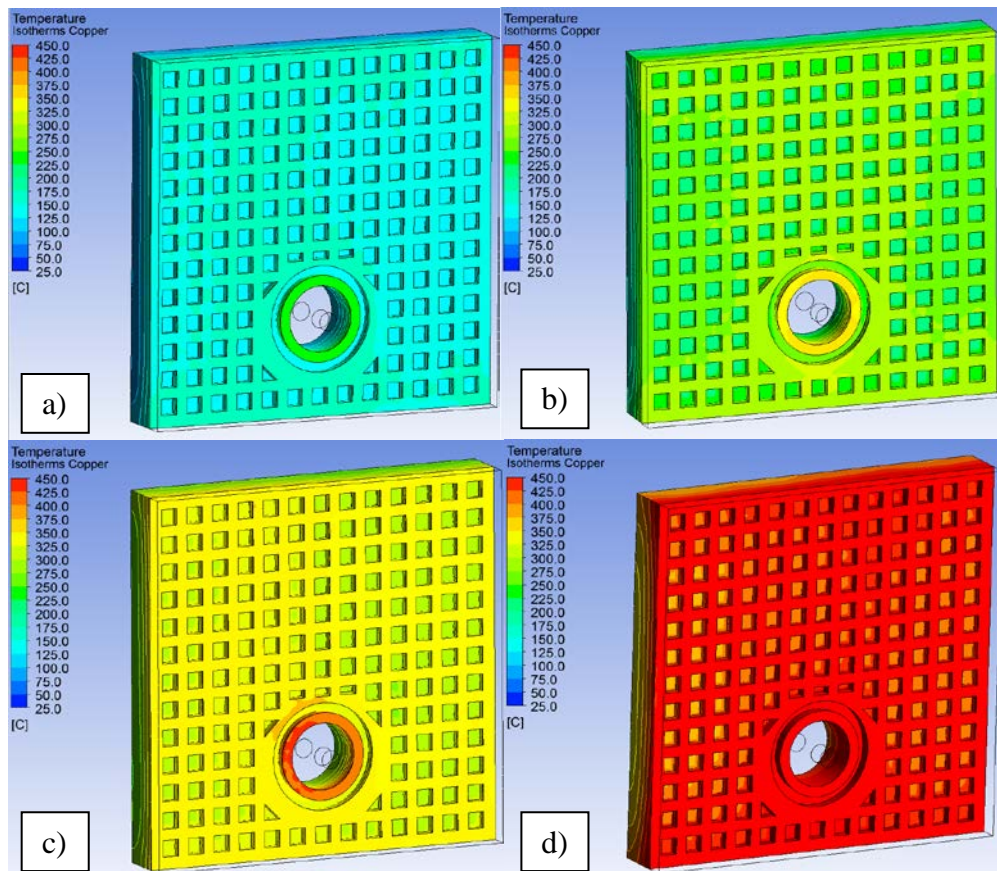

Figure 4 – Temperature isotherms for a) water, b) MEG, c) Pb-Bi and d) ISIS-B at 250 kW/m^2 applied hot-face heat flux and 2 m/s coolant velocity

In Figure 5 the performances of selected coolants at a velocity of 2 m/s are compared as a function of applied hot-face heat flux in order to elucidate their performance during a high heat flux 'event'. All of the coolants appear adequate to achieve at least a safety factor of 2 with respect to heat flux (i.e., 500 kW/m^2), without undue danger of boiling or immediate damage to the copper cooler due to melting. Testing would be required to explore the limits of nucleate boiling for MEG and ultimately the transition to film boiling. Results indicate that water will give the lowest copper hot-face temperature at all heat fluxes. Long term operation at hot-face temperatures over 450ºC for the alternative coolants would result in excessive copper oxidation as described previously. Continuous operation at high heat fluxes (e.g., 500 kW/m^2) with Pb-Bi, MEG and ISIS-B would require changes to reduce the rate of oxidation, i.e. a coating with nickel (Aniekwe & Utigard, 1999) or the use of an oxidation resistant alloy (Plascencia, Utigard, & Marín, 2005; Sanderson & Scully, 1971).
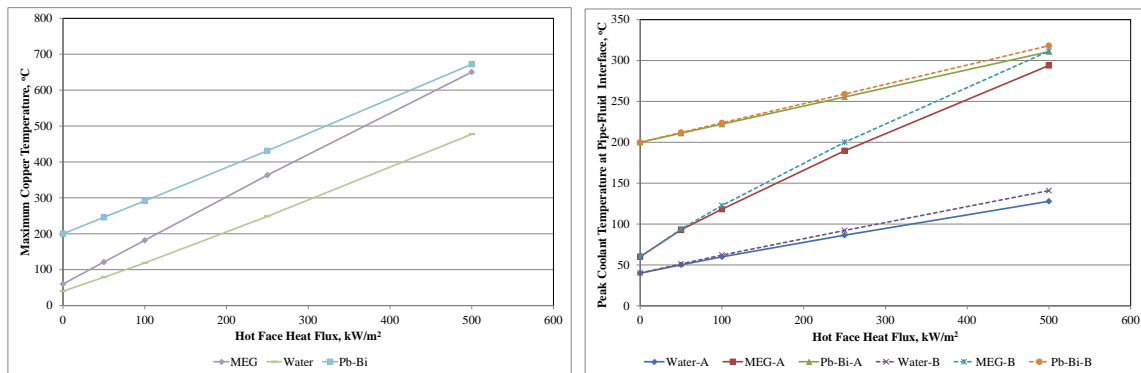

Figure 5 – Variation of peak coolant temperature at the internal pipe-fluid interface and maximum copper temperature at the hot-face vs applied hot-face heat flux for various coolants at a constant 2 m/s velocity

Pressure drop estimates for flow within the cooler have been obtained from the CFD results, which show that MEG would require a pumping pressure 1.4 times and Pb-Bi 8.4 times that of water.

Stresses at the pipe to cast around copper increase with temperature, due to the difference in the coefficients of thermal expansion. For example, stresses at the interface of the pipe to the copper, with MEG at 250 kW/m^2 are about 101 and 53 MPa for the pipe and copper, respectively. The nominal yield stress for the cast copper (0.2% offset) is approximately 69 MPa. If it is assumed that stress will vary linearly with the applied heat flux, then the maximum tolerable thermal load would be roughly 250*69/53=325 kW/m^2, with MEG with a bulk fluid velocity of 2 m/s. Stresses would be significantly higher if a nickel-copper alloy were to be employed instead of cupro-nickel. Materials of construction should be reviewed using 3D FEM modelling based on expected heat loads, as well as fluid properties and flow rates. Differential thermal stresses in pyrometallurgical operations have been treated in detail elsewhere (MacRae, 2015).

RESEARCH REQUIREMENTS

There is no single correct way to design a cooler or any particular coolant that is 'right' or 'best' under all circumstances. On the other hand there are certainly coolants that will or will not work with any given block design, system velocity or imposed heat flux.

Optimum Coolant Selection and Cooler Design

In order to make educated decisions in the selection of the optimal coolant for a given application or cooler design, the relative benefits of each coolant must be quantitatively compared to the risks posed and the required capital and operating costs. In order to perform this risk/benefit analysis, additional information is required about the behaviour of these coolants under normal, emergency and failure scenarios.

Heat Transfer Coefficients

Heat transfer coefficients under forced convection and boiling heat transfer should be verified experimentally and particularly the Critical Heat Fluxes for each type of coolant quantified as functions of: (i) operating temperature, (ii) system pressure and (iii) operating velocity, under controlled experimental conditions. Custom Nusselt number correlations applicable for these coolants flowing in serpentine coils should be developed to allow for better modelling of furnace cooling blocks.

Cooler Design

Furnace cooling blocks need to be custom engineered for the selected coolant. Increased coolant velocity might be required to obtain sufficiently high heat transfer coefficients and internal channel layout might need to be modified to reduce pressure drop or a higher operating pressure utilized. A higher internal area might be utilized in order to reduce block operating temperatures. Alternatively a different alloy (e.g., Cu-Be or non-copper designs) or a coating (e.g., nickel) might be utilized to protect the coolers from oxidation. It would be reasonable to construct and test coolers under extreme thermal load and real furnace conditions (PO_2, PSO_2, etc.) to explore the rate of oxidation/corrosion of different alloys and the impact of thermally induced stresses on their physical structure (i.e., cast-in-pipe to copper bond) and their long term heat transfer performance.

Flammability Testing

The flammability of different coolants should be tested under realistic conditions (e.g., warm coolant leaking onto a hot metal surface). The rate of energy released per unit area should be determined as a measure of fire intensity. Methods to reduce flammability or render the oil self-extinguishing should be explored (Kennedy et al., 2013), e.g. utilizing a 20% water-80% MEG solution might significantly reduce the risk of explosion from water, while simultaneously reducing the risk of fire (Carkin, Leon, & Weaver, 2011).

Explosion Testing

The explosivity of water is well demonstrated, while limited explosion testing has been conducted with alternative coolants like ISIS-B, MEG and Galden HT200. Larger scale tests should be conducted with quantities and conditions simulating realistic cooler failure scenarios.

Mintek Research Program

Mintek's Pyrometallurgy Division is currently embarking on a program to assess the use of METTOP´s ILTEC system (ionic liquid cooling technology) in furnace cooling systems, with the intention of replacing water in high-risk areas of the furnace. Mintek has a 3 MW DC arc furnace that presents a useful opportunity to demonstrate a safer cooling technology to the pyrometallurgical industry, in the course of testwork that is undertaken on a variety of commodities. It is seen as essential to have a demonstration system working on a pilot plant, before industry will be willing to adopt a new system. To date, funding has been applied to survey alternative cooling technologies. It is envisaged that a waterless tap-hole cooling system will be installed in 2016. Additionally, Mintek plans to incorporate this safer cooling technology into an early warning system for DC arc furnaces, based on existing in-house expertise on furnace modelling. Mintek would welcome collaboration around this area of improving furnace safety.

CONCLUSIONS

Water-metal interactions can produce true explosions capable of significant structural damage at distances over tens of metres.

Alternative coolants to water exist which appear to offer adequate cooling performance combined with a lower or negligible risk of explosions.

MEG is a cheap alternative with low flammability based on testing by Alcoa, but requires further safety analyses both with respect to rate of energy release in a fire and explosivity with liquid metal and matte. Pressure drop within the cooler was estimated to be 1.4 times that of water.

ISIS-B offers a non-flammable solution, which requires modifications to prevent excessive copper oxidation if operated at very high heat fluxes, and a coolant velocity two times higher than water, in order to achieve adequate heat transfer.

Pb-Bi is a cheap non-flammable coolant that will not generate any significant over pressure in the event of a leak; however, it must be maintained over its eutectic temperature of 123.5 $^{\circ}$C, and operated at a temperature of about 200 $^{\circ}$C, with a pressure drop over the cooler of about 8.4 times that of water at the same velocity.

Practical research should be conducted into furnace coolers and coolants in order to produce designs with greater levels of intrinsic safety.

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