Non-water-based metal tap-hole cooling – a safer alternative

M.W. Kennedy¹,², A. MacRae³, P. Nos⁴, and F. Olesen⁵

¹NTNU, Norway
²ProVal Partners, Switzerland
³MacRae Technologies, USA
⁴Termek Technology, Norway
⁵Elkem Bjølvfossen, Norway

Modern nonferrous smelting furnaces are designed for both high-intensity operation and long campaign lives. To achieve these two objectives, these vessels often incorporate extensive use of water cooling, including at the slag and metal tap-holes. Water coming into contact with liquid metal is a well-known danger, particularly at the metal tap-hole, due to the frequent proximity of workers. This paper examines the use of alternative coolants, having lower explosion potential at the metal tap-hole, with a focus on mixtures with very high contents of monoethylene glycol (MEG) and low water content. Finite element and analytical modelling are combined with industrial information to explore the performance of potential coolants, and recommendations are given regarding the path to greater implementation.

Keywords: coolant, cooler, furnace, safety, tap-block.

INTRODUCTION

The refractories in modern high-intensity furnaces are frequently stabilized using active cooling systems in order to achieve higher productivity and longer campaign lives (Kennedy, MacRae, and Haaland, 2016). The use of water cooling for both refractory and other furnace components such as electrode columns has led to incidents of water-metal explosions worldwide (Oterdoom, 2014a, 2014b; Tveit et al., 2006; Robinson, 2004), i.e. boiling liquid expanding vapour explosions (BLEVEs) (Abbasi and Abbasi, 2007). The energy release and level of damage produced by such BLEVEs is comparable to high explosives (Babaitsev and Kuznetsov, 2001).

As a result of the risks associated with BLEVEs, interest has developed in improved the detection of unsafe conditions using advanced modelling/monitoring (Eidem, Egeland, and Baumann, 2013; Hopf, 2014; Gunnewiek et al., 2008; Gerritsen et al., 2009; Sadri, Gebski, and George-Kennedy, 2008), the use of alternative coolants to reduce the severity of explosions (Kennedy et al., 2013, 2015; Filzwieser, Konetshink, and Dreyer, 2014), and better designs and operating practices (Steenkamp et al., 2016; Nelson and Hundermark, 2016) to improve tap-hole fundamental reliability.

Given that tap-holes are where ‘the man meets the metal’, safety considerations in this region of the furnace are particularly critical, due to the proximity of personnel. Automated equipment may someday remove people from the tap-hole area, but until such time, alternatives that have a lower explosive potential than water should be explored. This paper will focus on the use of coolants other than water, primarily on monoethylene glycol (MEG) and MEG-water mixtures, which represent a practical ‘open source’, previously published (Kennedy et al., 2013) option available to replace water in tap-holes and other safety-critical applications. An intensely cooled slag tap-hole will be used as a simple geometry for finite element modelling (FEM) and discussion. Some
useful analytical models for comparing coolants and operating conditions will be explored and a path towards greater implementation presented.

**COMPARISON OF COOLANTS**

Historically, there has been a bias against coolants other than water in metallurgical applications, with the implicit assumption that alternative coolants could not meet the demanding duty, that the cost of such coolants was too high, or that the risks associated with other properties, e.g. flammability or toxicity, were too great. These assumptions will be explored with reference to a number of coolants previously applied in the pyrometallurgical industry.

The authors often use the Colburn equation (Colburn, 1933) to obtain heat transfer coefficients for furnace coolants, specifically due to the fact that it tends to underestimate the true heat transfer coefficient, and is therefore considered conservative from an engineering standpoint. The Colburn equation is also convenient in that it uses bulk coolant properties, reducing the complexity of the computations:

\[
Nu = 0.023 Re^{0.8} Pr^{1/3} \quad [1]
\]

where:

\[
Nu = \frac{hD_h}{k} \quad [2]
\]

\[
D_h = \frac{Channel \ area}{Channel \ perimeter} \quad [3]
\]

\[
Re = \frac{\rho v D_h}{\mu} \quad [4]
\]

\[
Pr = \frac{C_p \mu}{k} \quad [5]
\]

and \( h \) is the average turbulent forced convection heat transfer coefficient between the channel wall and the bulk coolant (W/m²·K), \( D_h \) is the hydraulic diameter of the channel (m), \( k \) is the average thermal conductivity of the channel (W/m·K), \( D_h \) is the hydraulic diameter of the channel (m), \( k \) is the average thermal conductivity of the channel (W/m·K), \( C_p \) is the mean heat capacity of the coolant (J/kg·K), \( \rho \) is the average bulk coolant density (kg/m³), and \( v \) is the average velocity in the cooling channel (m/s).

Table I lists some alternative coolants previously applied in the metallurgical industry (Kennedy et al., 2013, 2015; Filzwieser, Konetshink, and Dreyer, 2014). Applying Equation [1] to a typical cast-in pipe with a 0.035 m nominal inside diameter allows the forced convective heat transfer coefficient to be estimated as a function of fluid properties and velocity. 60°C has been selected as a standard temperature to present the data for the alternative coolants, due to their higher low-temperature viscosities. Table I indicates that velocities from 2 to >13 times that of water would be required to achieve half of the water heat transfer coefficient, emphasizing the fact that water is a remarkably effective coolant.

From the data in Table I, it can be seen that 80 and 90% MEG-water mixtures by weight are the next best coolants to water from a convective heat transfer coefficient perspective, requiring 5.8 and 7.3 m/s at 60°C, to achieve a ‘h’ value one half that of water at 3 m/s and 40°C. To put this in perspective, for a surface heat flux of 400 kW/m², this translates to an increase in copper interface temperature from 81°C with water at 3 m/s, up to 142°C for 80 and 90% MEG by weight, at 5.8 and 7.3 m/s respectively.
Table I. Typical heat transfer properties of various coolants previously applied in pyrometallurgical furnace cooling (two-phase fluids marked with bold-blue text, single-phase marked with grey background).

| Cooling Fluid | Approximate Range of Operation Min/Max °C | Temp for Ref. Data °C | Density, kg/m³ | Heat Capacity, J/kg K | Thermal capacity up to the normal boiling point, MJ/m³ | Thermal Conductivity, W/m K | Viscosity, mPa s | Prandtl Number | Fluid Velocity | Reynolds Number | Nusselt Number | 35 mm Tube Forced Convection Heat Transfer Coefficient, W/m² K |
|---------------|------------------------------------------|-----------------------|-----------------|-----------------------|--------------------------------------------------------|-----------------------------|-----------------|----------------|----------------|----------------|---------------|----------------|--------------------------------------------------|
| Water (NIST)  |                                          |                       |                 |                       |                                                         |                             |                 |                |                |                |               |                |                                                 |
| MEG (Dowtherm 400) 80% | -29/176.6 | 60 | 1088 | 2544 | 382 | 0.260 | 5.7 | 56 | 10.5 | 69878 | 662 | 4905 |
| MEG (Dowtherm 400) 90% | -29/176.6 | 60 | 1110 | 2610 | 217 | 0.270 | 3.4 | 33 | 7.3 | 83227 | 637 | 4905 |
| Galden HT 2M | -30/300 | 60 | 1018 | 295 | 0.065 | 2.1 | 36 | 17.2 | 499440 | 2729 | 4905 |
| Dowtherm A | -15/400 | 60 | 1024 | 542 | 0.132 | 1.7 | 22 | 11.5 | 249792 | 1502 | 4905 |
| MEG (MEG*) | -15/340 | 60 | 1088 | 2644 | 57 | 0.260 | 5.7 | 56 | 10.5 | 69878 | 662 | 4905 |
| Dowtherm A | -15/400 | 60 | 1024 | 542 | 0.132 | 1.7 | 22 | 11.5 | 249792 | 1502 | 4905 |
| Dowtherm A | -15/400 | 60 | 1024 | 542 | 0.132 | 1.7 | 22 | 11.5 | 249792 | 1502 | 4905 |
| MEG (Dowtherm 400) 80% | -29/176.6 | 60 | 1088 | 2544 | 382 | 0.260 | 5.7 | 56 | 10.5 | 69878 | 662 | 4905 |
| MEG (Dowtherm 400) 90% | -29/176.6 | 60 | 1110 | 2610 | 217 | 0.270 | 3.4 | 33 | 7.3 | 83227 | 637 | 4905 |
| Galden HT 2M | -30/300 | 60 | 1018 | 295 | 0.065 | 2.1 | 36 | 17.2 | 499440 | 2729 | 4905 |
| Dowtherm A | -15/400 | 60 | 1024 | 542 | 0.132 | 1.7 | 22 | 11.5 | 249792 | 1502 | 4905 |
| MEG (MEG*) | -15/340 | 60 | 1088 | 2644 | 57 | 0.260 | 5.7 | 56 | 10.5 | 69878 | 662 | 4905 |
| Dowtherm A | -15/400 | 60 | 1024 | 542 | 0.132 | 1.7 | 22 | 11.5 | 249792 | 1502 | 4905 |
| MEG (Dowtherm 400) 80% | -29/176.6 | 60 | 1088 | 2544 | 382 | 0.260 | 5.7 | 56 | 10.5 | 69878 | 662 | 4905 |
| MEG (Dowtherm 400) 90% | -29/176.6 | 60 | 1110 | 2610 | 217 | 0.270 | 3.4 | 33 | 7.3 | 83227 | 637 | 4905 |
| Galden HT 2M | -30/300 | 60 | 1018 | 295 | 0.065 | 2.1 | 36 | 17.2 | 499440 | 2729 | 4905 |
| Dowtherm A | -15/400 | 60 | 1024 | 542 | 0.132 | 1.7 | 22 | 11.5 | 249792 | 1502 | 4905 |
| MEG (MEG*) | -15/340 | 60 | 1088 | 2644 | 57 | 0.260 | 5.7 | 56 | 10.5 | 69878 | 662 | 4905 |
| Dowtherm A | -15/400 | 60 | 1024 | 542 | 0.132 | 1.7 | 22 | 11.5 | 249792 | 1502 | 4905 |

Considering the total thermal capacity of the coolants on a volumetric basis from their typical operating temperature (shown in Table I) up to their normal boiling points at 1 atmosphere for two-phase fluids, or decomposition temperatures for the single-phase fluids, it can be seen that the alternative coolants have thermal capacities from 75 to 200% that of water, i.e. the greater thermal range of the alternative fluids greatly compensates for their lower heat capacity or density.

In normal design practice, coolers are designed to avoid boiling; however, the transition to nucleate boiling greatly improves heat transfer in a thermal crisis until the burnout or critical heat flux (Çengel and Ghajar, 2011), at which point film boiling or ‘steam blanketing’ occurs, and the cooler will in most cases heat until failure. Higher fluid velocities will strip nucleated bubbles from the heat transfer interface, delaying the onset of film boiling at high fluid velocities, making the exact prediction of the critical heat flux (CHF) challenging and the subject of a great deal of research (Chang and Baek, 2003). The higher velocities used with alternative coolants therefore come with some additional benefit in terms of higher CHF.

The improved heat transfer coefficients of two-phase fluids in nucleate boiling represent a normally unutilized yet significant safety factor, while the lack of boiling and extremely high thermal capacity of some single-phase fluids is another. In general, the authors prefer two-phase fluids, as they boil and do not break down or create solid deposits during periods of extreme but sub-CHF heating. The non-boiling heat transfer coefficients of the two-phase fluids are marked in Table I with bold blue text, while the single-phase fluids are marked with a grey background.

Alcoa previously applied Galden HT (a two-phase fluorinated and completely non-flammable oil) in the Carbothermic Aluminium project, but discontinued its use due to the formation of small quantities of HF after thermal decomposition and reaction with atmospheric moisture. Galden has proven to be non-explosive during both special laboratory tests (Carkin, Leon, and Weaver, 2011) and pilot plant operation at highly elevated temperatures with liquid aluminium present. Alcoa has replaced Galden with a MEG-water coolant containing 10% water by weight (Kennedy et al., 2013). It is further noted that while MEG with 10% water is minimally flammable, MEG with 20% is considered non-flammable (Hull et al., 2008).

A review of coolant selection criteria has been presented elsewhere (Kennedy et al., 2015). In general, there are no perfect coolants combining both excellent heat transfer and physical properties with zero inherent risk. For example, while water is non-toxic,
inexpensive, and an excellent heat transfer fluid, it has a propensity to generate dangerous overpressures when mixed with metal, possibly due to the combination of high vapour pressure and its excellent heat transfer properties. Galden HT, while non-flammable is quite expensive (tens of dollars per litre), and can form toxic decomposition products as noted previously, in addition to having relatively poor heat transfer properties. While low in cost, many of the synthetic single-phase oils are highly flammable and require significant pumping velocities to achieve an adequate heat transfer coefficient for high-performance applications. MEG combined with 10 or 20 wt% water, on the other hand, represents a good compromise in terms of price (representative price of $5 per litre), with low or no flammability, no especially toxic decomposition products, and good heat transfer properties at moderate fluid velocities. In the next section, a comparison will be made between water cooling and MEG with 20% by weight water for a slag tap-hole insert, and issues associated with its implementation will be discussed.

**FEM MODEL RESULTS AND DISCUSSION**

A FEM model has been executed using Ansys CFX on a simplified slag tap-hole insert design, as shown in Figure 1. The assumed heat transfer surfaces are highlighted by the green mesh in Figure 1, with the uncoloured surface assumed to be insulated in order to give a pessimistic analysis. Heat fluxes of 200 and 400 kW/m² have been applied to several different cases, using both water at 3 m/s with an inlet temperature of 30°C, and an 80:20 weight ratio glycol-water mixture with an inlet temperature of 45°C at both 4 and 6 m/s.

![Figure 1. Simplified slag tap-hole insert.](image)

Details of the mesh are shown in Figure 2. Thermal results for the copper are shown in Figure 3 and for the coolant surface temperature in Figure 4. Some key information is plotted in Figure 5, with the data provided in Table II.
Figure 2. 3D cooler mesh showing inflation layers at fluid-solid interfaces.

Figure 3. Copper cooler temperatures for both 30°C water inlet at 3 m/s (left) and 45°C 80:20 MEG-water inlet at 6 m/s (right) at 400 kW/m² applied flux.

Figure 4. Coolant surface temperatures for both 30°C water inlet at 3 m/s (left) and 45°C 80:20 MEG-water inlet at 6 m/s (right) at 400 kW/m² applied flux.
Figure 5. Peak fluid and copper surface temperatures as functions of applied heat flux for 80:20 wt. ratio MEG-water mixture at 6 m/s with a 45°C inlet temperature, and for water at 3 m/s and 30°C inlet temperature.

Table II. Comparison of coolant performance, water versus 80:20 MEG-water ratio by weight for the slag tap-hole insert shown in Figures 1-4.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Fluid Velocity (m/s)</th>
<th>Inlet Temp. (°C)</th>
<th>Heat Flux (kW/m²)</th>
<th>Maximum Cu Temp. (°C)</th>
<th>Maximum Fluid Temp (°C)</th>
<th>Exit Fluid Temp (°C)</th>
<th>Cooler Delta Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>3</td>
<td>30</td>
<td>0</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>185</td>
<td></td>
<td>59</td>
<td>88</td>
<td>43</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>351</td>
<td></td>
<td>88</td>
<td>43</td>
<td>43</td>
<td>64</td>
</tr>
<tr>
<td>80/20 MEG/water</td>
<td>4</td>
<td>45</td>
<td>0</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>230</td>
<td></td>
<td>112</td>
<td>52</td>
<td>52</td>
<td>127</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>432</td>
<td></td>
<td>176</td>
<td>58</td>
<td>58</td>
<td>127</td>
</tr>
<tr>
<td>80/20 MEG/water</td>
<td>6</td>
<td>45</td>
<td>0</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>217</td>
<td></td>
<td>96</td>
<td>50</td>
<td>50</td>
<td>285</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>409</td>
<td></td>
<td>144</td>
<td>54</td>
<td>54</td>
<td>285</td>
</tr>
</tbody>
</table>

The impact of the change of coolants and coolant velocities can be observed by examining Figures 3–5 and Table II. The use of 80:20 MEG-water mixture increased the peak copper temperature from 351 to 409°C, a change of 58°C, of which 43°C is due to the change in heat transfer coefficient and 15°C due to the change of the inlet temperature. A change in coolant velocity for the 80:20 MEG-water mixture decreased the peak copper temperature from 432 to 409°C and the peak coolant temperature from 176 to 144°C, while increasing the pressure drop across the cooler from 127 kPa to 285 kPa, compared to 64 kPa for water. Assuming that the entire cooling system is designed to allow for the higher coolant flow required for alternative coolants, there is no need to use more than the standard 6 bar system design pressure in either case. The data in Table II indicates that a coolant velocity of 6 m/s would be adequate for a cooler with a design peak heat flux of approximately 400 kW/m² with a risk of minor nucleate boiling.
at the final bends, as shown by the red regions in Figure 4. Sustained fluxes over 400 kW/m² would lead to localized nucleate boiling within the piping and hot-spots in the copper subject to long-term recrystallization and corrosion. Higher heat fluxes would demand an additional increase in coolant velocity, with 13.9 m/s giving the same ‘h’ value as for water, and a pressure drop of about 15 bar across the cooler.

It is to be noted that direct contact between liquid metal and cooled copper, e.g. due to a total loss of refractory, can produce heat fluxes of several MW/m² and burnout can rarely be avoided in such cases. Extensive monitoring of fluxes and temperatures is required to ensure the safe evacuation of personnel under such conditions.

Commercial use of Oil-cooled Tap-holes
Termek supplied XCELTHERM 600 oil-cooled metal tap-holes to Elkem for use on Bjølvefossen’s FeSi furnace number 5 in August 2012, and on furnace 1 in the fall of 2015. The installations have functioned reliably in commercial operation and are not considered ‘experimental’ in nature. Significant knowhow is required to correctly design cooling systems for alternative coolants due to limited coolant volumes, higher operating temperatures, higher velocities, possible flammability, and other changes when compared to water cooling. Some design issues have been previously discussed elsewhere (Kennedy et al., 2015, 2013). The reader is recommended to seek experienced system designers should they be interested in using alternative coolants to water.

PATH FORWARD

Issues related to the implementation of alternative coolants have been discussed in some detail elsewhere (Kennedy et al., 2015), and two key points are repeated below:

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, and 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.

It is hoped that proactive furnace owners will perform such tests and move forward with the implementation of alternative coolants in high-risk furnace areas, such as around tap-holes.
CONCLUSIONS

Alternative coolants to water can be safely and economically applied in critical metallurgical applications if their properties are correctly accounted for in the cooler and cooling system design. This typically requires higher flow velocities and slightly elevated inlet temperatures and considerations of the limited storage of coolant within the circuits.

In this study, 80:20 and 90:10 MEG-water mixtures were shown to be the second- and third-best heat transfer fluids (of those examined) relative to water from a heat transfer coefficient perspective. MEG-water mixtures would be economical options in critical locations where water might be considered too dangerous due to the explosion risk. Non-toxic and non- or low-flammability alternatives to water coolant exist, but a need persists for practical testing of the reduction of explosive force when large quantities of coolant are injected into molten metal. Practical worst-case flammability tests should also be developed, along with the use of oil additives for flammable oils in order to reduce flammability (Wright Mowery, and Lepera, 2000).

REFERENCES


Mark William Kennedy  
*Technology Leader, Elkem Foundry Technology (as of June 1, 2018)*  
Dr Kennedy has worked in metallurgical process engineering with a number of metals (Mg, Al, Ni/FeNi, Cu, Zn, *etc.*) in research, production and projects over more than 25 years, and for a variety of companies, including ProVal Partners, Elkem, Falconbridge, and Noranda. He has degrees in chemical and metallurgical engineering as well as materials science, from universities in Canada (Waterloo and McGill), Norway (NTNU), and Sweden (KTH).