Closing your slag tap-hole

S.C. Essack

Tenova Pyromet has designed a slag flow control valve that throttles the flow of slag in order to control the tapping rate. In addition, the valve has proved to be a reliable tool for closing the furnace during normal operation as well as emergency conditions.

The valve makes use of a water-cooled copper element that is hydraulically operated and attached directly to the slag tap-hole. The equipment is compact, simple to maintain, and cost-effective to purchase and install. It can be retrofitted to most existing slag tap-holes with minimal modifications.

During the development phase, finite element method (FEM) and computational fluid dynamics (CFD) software was extensively used to model predicted operating conditions and to optimize the design. By using CFD, it was possible to understand the flow patterns inside the copper and to optimize these to improve overall performance.

The slag valve was installed and commissioned in 2011/2012 on a 12 MW furnace as part of a new mineral wool plant in the USA. It has performed well since its installation despite operating under conditions in excess of the original design criteria. During the first 6 months of operation it quickly became the preferred method of closing the tap-hole, a few minor changes have been made to the installation in order to cope with the increased heat load and much higher frequency of use.

Keywords: slag valve, flow control, mineral wool, water-cooled copper, slag tapping

Introduction

During 2010, TENOVA was awarded the contract to design and supply a 12 MW mineral wool furnace in the USA. This furnace required a slag flow control device for each of the two tap-holes. This provided the opportunity to develop a slag flow control valve based on previous experience. A robust design was required, as this is a continuous tapping process and the demands placed on the equipment are extreme. In addition, space constraints in the tap-hole area of a relatively small furnace meant a compact design that is easy to maintain were a requirement upfront.

Mineral wool manufacture

Mineral wool is manufactured by spinning molten aluminosilica slag into fibres. Fibres can be manufactured by blowing or spinning. Fibre lines can be fed by a coke-fired cupola or by an electric arc furnace. The mineral wool fibres are deposited in layers and may be combined with a resin binder, pressed, and baked depending on the final product. Mineral wool has very good thermal and sound insulation properties.

Mineral wool is also referred to as slag wool or stone wool, depending on the raw material that is used. Slag wool is made from blast furnace slag, which is a by-product of steel production, while stone wool is made using aluminosilicate (basalt) rock as the raw material (Crane and McLaren, 2008).

Depending on the raw material used and the final processing method a wide variety of products can be made servicing the following roles (Saint-Gobain ISOVER, 2008 and Eurima, 2011):

- Fire protection
- Ceiling boards/dry walling
- Filtering and gasket elements
- Growth medium in hydroponics
- Fibre addition to reinforce various plastics, friction materials, and coatings.

The typical slag composition and operating temperature range of a so-called stone wool are shown in Table I.
Table I. Typical slag composition and liquidus temperatures

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Formula 1</th>
<th>Formula 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag liquidus temperature</td>
<td>°C</td>
<td>1340</td>
<td>1290</td>
</tr>
<tr>
<td>Tapping temperature range</td>
<td>°C</td>
<td>1450 - 1550</td>
<td></td>
</tr>
<tr>
<td>SiO₂ [% w/w]</td>
<td></td>
<td>41.04</td>
<td>40.77</td>
</tr>
<tr>
<td>Al₂O₃ [% w/w]</td>
<td></td>
<td>19.17</td>
<td>18.87</td>
</tr>
<tr>
<td>MgO [% w/w]</td>
<td></td>
<td>6.27</td>
<td>5.64</td>
</tr>
<tr>
<td>CaO [% w/w]</td>
<td></td>
<td>18.83</td>
<td>18.98</td>
</tr>
<tr>
<td>Fe₂O₃ [% w/w]</td>
<td></td>
<td>0.43</td>
<td>0.40</td>
</tr>
<tr>
<td>MnO [% w/w]</td>
<td></td>
<td>9.61</td>
<td>10.12</td>
</tr>
<tr>
<td>TiO₂ [% w/w]</td>
<td></td>
<td>0.21</td>
<td>0.14</td>
</tr>
<tr>
<td>Na₂O [% w/w]</td>
<td></td>
<td>0.48</td>
<td>0.70</td>
</tr>
<tr>
<td>K₂O [% w/w]</td>
<td></td>
<td>1.38</td>
<td>1.38</td>
</tr>
<tr>
<td>P₂O₅ [% w/w]</td>
<td></td>
<td>0.06</td>
<td>0.018</td>
</tr>
</tbody>
</table>

The slag viscosity is plotted as a function of temperature for these two slag compositions in Figure 1.

![Viscosity vs Temperature](image)

*Figure 1. Slag viscosity as a function of temperature (after Muchena, 2012)*

The challenge

**Functional requirements**

The slag valves are designed to modulate the flow of slag. This is a requirement imposed by the downstream spinning equipment. In order to maintain consistent fibre quality, the slag stream must be consistent and controlled.

The client specified that the slag valve should also be able to shut the slag tap-holes under emergency conditions, freezing slag inside the tap-hole and closing the furnace.
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The mineral wool furnace is tapped on a continuous basis with a scheduled stop approximately twice a month during which maintenance can be performed. This continuous operation subjects all equipment in the tap-hole area, including the slag valve, to very high heat loads and does not allow for frequent maintenance.

As with many furnaces space is at a premium in the tap-hole area. Since this is a relatively small furnace with two closely spaced tap-holes, the problem of space was compounded.

Figure 2 shows the slag tap-hole equipment, which consists of the following components:

- Slag tap-hole inner block
- Slag valve assembly
- Tap-hole faceplate
- Integrated valve guide
- Steel flange.

The dimensions and operating data are shown in Table II.

Table II. Equipment dimensions and operating data

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap-hole diameter</td>
<td>mm</td>
<td>38</td>
</tr>
<tr>
<td>Slag valve dimensions (incl cylinder) – length × width × height</td>
<td>mm</td>
<td>275 × 100 × 780</td>
</tr>
<tr>
<td>Slag flow rate</td>
<td>t/h</td>
<td>6</td>
</tr>
</tbody>
</table>

The slag tap-hole inner block and tap-hole faceplates are both water-cooled copper elements. These pieces of equipment using a freeze lining design to protect the tap-hole equipment. The water cooling channels are designed to minimize the risk of explosion in the unlikely event of a burn-through of the tap-hole cooling elements. The water cooling circuits have fairly long fixed piping sections extending outward from the copper equipment, in order to move the flexible hoses away from the high radiation and potential slag splash zone. The flexible pipes, which unlike the fixed piping cannot withstand high temperatures, are thus protected from the very high heat loads, extending their life.

The guide for the slag valve is integrated into the faceplate design. This guide acts as a mechanical limit for excessive horizontal movement of the slag valve.
Consistent flow of slag to the spinners is paramount, so gate position changes are made incrementally. The slag valve position is actuated remotely by a set of push-button controls. The control of the slag valve is a simple operator-controlled task. A combination of live video feedback and basic feedback from the spinner is used by the furnace operators to decide on what changes must be made to the position of the slag valve. If an emergency shut is required, the furnace operator lowers the slag valve completely. This action slows the flow of slag and the water-cooled elements then freeze the slag inside the tap-hole, effectively closing the furnace. The slag valve can be set up to close automatically in the event of a furnace trip should the specific operation warrant this action.

The steel flange shown in Figure 2 is installed in order to facilitate tap-hole repair and replacement from the outside of the furnace. This flange is designed to act as a lifting support frame when the inner block is removed for maintenance or replacement and during first installation.

Modelling the design

A model of the slag valve was created using ANSYS software. A combination of FEA and CFD modelling was used to predict the equipment temperatures. This paper only includes the results of the CFD modelling.

The heat transfer in the slag valve is largely due to two mechanisms: (1) slag in contact with the copper, and (2) cooling water on the copper. The heat transfer from the slag was represented by a convection heat transfer coefficient, on two faces of the copper. The heat transfer between the copper and the water in the internal water passages was modelled using the ‘conservative interface flux’ condition in ANSYS. The heat transfer on the remaining external faces of the copper is negligible compared with the other heat loads. No freeze lining was modelled on the copper. This represents the moment that the molten slag comes into first contact with the new copper valve.

A thin freeze lining in the region of 2 mm has been reported to form almost instantly (Nourse, 2014), but the purpose of the model was to confirm that the slag valve would withstand the highest heat load incidents.

Table III. Boundary conditions used for CFD analysis

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat transfer mechanism</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat load applied – (convection heat transfer coefficient)</td>
<td>W/m²K</td>
<td>2034</td>
</tr>
<tr>
<td>Slag Temperature</td>
<td>°C</td>
<td>1427</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference pressure</td>
<td>Atm.</td>
<td>1</td>
</tr>
<tr>
<td>Inlet normal speed</td>
<td>m/s</td>
<td>2</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>°C</td>
<td>45</td>
</tr>
<tr>
<td>Outlet pressure</td>
<td>Pa</td>
<td>0</td>
</tr>
</tbody>
</table>

As shown in Figure 3 the initial simulations predicted temperatures in excess of 627°C (900K). As copper begins to lose its mechanical strength at approximately 360°C (Matweb, 1999), this temperature profile is unacceptable.
By optimizing the design of the flow channels inside the slag valve, the simulated temperatures were brought down to within the acceptable range. Figure 4 shows that there are small areas closest to the contact area with the slag where the expected copper temperatures are at the limit of the acceptable range.
The slag valve is subjected to the force of the slag flow and the force of closing the valve against frozen slag that may build up during the tapping cycle. Since these forces are relatively low, the acceptable design temperature for this specific case is higher than for other copper equipment typically specified by TENOVA.

The slag valve is a consumable item and is expected to be replaced periodically as it wears. The wear pattern on the valve is expected to be asymmetrical with the hot face side wearing faster than the cold face. The slag valve has been designed with enough material between the water channel and the slag to allow for 30 mm of wear. Once the valve has worn back by that amount it must be replaced. At this stage there will still be a safe amount of copper between the water and the slag.

Installation and operation

The equipment was installed at a plant in the USA at the end of 2011 and the furnace was switched-in during the first quarter of 2012. Reports of initial operation were favourable, and shortly after switch-in the slag valve became the preferred method of closing the furnace, rather than the clay gun. The tap-hole is reopened directly by drilling, with lancing often not required at all.

In Figure 5 the slag valve can be seen in operation. Note the uniform slag stream with the slag valve partially closed. Figure 5 also shows how the flexible piping is largely shielded by surrounding equipment which reduces the heat load (most flexible piping is not visible in this picture).

Figure 5. Installed slag valve in operation

Figure 6 is a photograph taken of the slag valve to show the wear pattern that was seen after some months of operation. The horizontal striations are a result of the furnace operator cleaning the valve of frozen slag. Overall the wear on the slag valve is minimal, which supports the view taken on the acceptable temperature limits when modelling this piece of equipment.
It has not been possible to collect data of the temperature profile inside the slag valve to date. However, the measured slag temperatures reported from the plant (Mitchell, 2014) have, on average, been 137°C higher than the maximum temperature expected and used in the modelling. These higher operating temperatures have not materially affected the life of the slag valve. The consumable portion is replaced at 12-week intervals, which is consistent with initial expectations.

**Modifications made after installation**

Approximately 6 months after switch-in, the performance of the slag valves was evaluated. It was found that there was some minor deformation in the support structure of the valve assemblies. This increased the clearance between the tap-hole faceplate and the slag valve and increased the time it was taking to close the slag tap-holes. These support structures were replaced with an alternative design, and there have been no further reported problems.

In addition, the client was experiencing accelerated wear on the seals of the hydraulic cylinder on one of the tap-holes. The cause was traced to localized degradation of the hydraulic fluid (water glycol) since the hydraulic supply pipes are routed past tap-hole one to reach tap-hole two. This was remedied by adding a much longer shield and water-cooling the shield to protect the slag valve assembly. Shielding was also added to protect the hydraulic fluid supply piping.

Figure 7 shows the slag tap-hole assembly with the longer water-cooled shield. Note how the shield extends to the top of the valve guide on the tap-hole faceplate. This extended shield protects the hydraulic cylinder rod and seals from the high radiant heat loads.
What value does the slag valve add?
As a means of closing a slag tap-hole, the slag valve offers a substantial saving in terms of equipment costs. The typical cost of a slag valve assembly is around 15% of that of a mudgun machine. In addition to the cost saving, the space required for a slag valve is substantially less than for a mudgun. The equipment does not require operating space since it is permanently attached to the shell.

For a very low capital investment, the slag valve allows the furnace to be remotely closed under normal conditions and under emergency conditions.

Conclusion
The use of computational modelling allowed for a relatively simple design optimization process and resulted in a design that performed well on the first installation. This design is well suited to slag tapping operations where there is a need to modulate slag flow, and has proved to be a reliable and robust method of shutting the slag tap-hole. This piece of equipment can easily be installed as an emergency back-up to most slag tap-holes. It can also be installed in order to add a level of control upstream of slag granulation processes and improve their consistency and safety.

References


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Saskia is a senior development engineer for the Technology department. She has played various roles within Tenova Mining and Minerals (Pty) Ltd since joining in 2007. These roles facilitated her acquiring a wide range of experience in design, project administration and execution, studies and marketing related activities. A large percentage of her experience has been with international clients (Britain, China, Italy, Korea, Norway, Turkey, USA.).

Prior to joining Tenova Mining and Minerals, Saskia had a bursary from Atlas Copco where she first experienced to the practical aspects of engineering and various production industries (mainly automotive assembly lines and tooling and mining equipment production). A two year stint as a bookkeeper introduced her to the world of finance, South African tax law and client/supplier relations.