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Tap-Hole Life Cycle Design Criteria: A Case Study Based on Silicomanganese Production

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Managing the tapping of furnaces is a challenge to most furnace operators. As a hole is made in the refractory lining and re-filled with clay, several times a day, the tap-hole is one of the weak spots in the refractory lining. Tap-hole failures are high-risk events, and steps should be taken to minimize the risks. Designing for the life–cycle of the tap-hole is proposed and discussed as a way of minimizing the risks associated with tap-hole failure. Design criteria are proposed not only for a total reline and normal operation but also for emergency conditions, as well as maintenance, and repair of the tap-hole. The criteria are discussed in the context of silicomanganese production in South Africa.

INTRODUCTION

All pyrometallurgical smelters have tap-holes, through which liquid metal, matte and/or slag, are tapped at regular intervals (typically 3–4 h on a 48-MVA (Mega Volt-Ampere) submerged arc furnace producing silico-manganese). From a furnace containment perspective, the tap-hole area is one of the high-wear, and therefore high-risk, areas. Tap-hole failures are high-risk events due to consequential damages caused by a run-out, i.e. damage to equipment, risk to human safety, and loss in production. As an example: in 2014, a furnace tap-hole failure at Koniambo nickel smelter resulted in damage in excess of US$3 million, and nearly a full year outage, as a complete rebuild of the furnace was required after the failure.[1]

BACKGROUND

In 2014, the Southern African Institute of Mining and Metallurgy (SAIMM) hosted the 1st Furnace Tapping conference. Although intended as a local event, 20% of the 203 delegates were from countries outside South Africa, as indicated in Fig. 1a. The global interest in the topic was further illustrated by the fact that only 10 of the 19 papers included in the proceedings,[2] had first authors from South Africa. The importance of the topic to industry was illustrated by the fact that seven of the papers presented were presented by furnace operators, as indicated in Fig. 1b.

It was concluded from the discussions at the event, that the total life cycle of furnace tap-hole management should be addressed during the furnace design phase. That is often not the case, with furnace designers only focussing on initial installation and normal operation. The paper presented here aims to provide a set of criteria to assist in total life-cycle design of furnace tap-holes.

DISCUSSION

Tap-Hole Life Cycle

The furnace tap-hole life cycle is illustrated in Fig. 2. When a furnace is lined for the first time, or completely relined during the course of normal operation, the tap-hole installation forms part of the total refractory installation. The tap-hole is opened and closed as part of normal operations, and, during this time, starts to wear. Two high-wear areas exist: (1) the hot face of the tapblock, which is the interface between the refractory material and the liquid metal, matte and/or slag,[3–5] and (2) the cold face, which is the interface between the refractory material and the drill-and-mudgun[6] (or other equipment, i.e. a slag flow control valve[7]) used to open and close the tap-hole. Between taps, the tap-

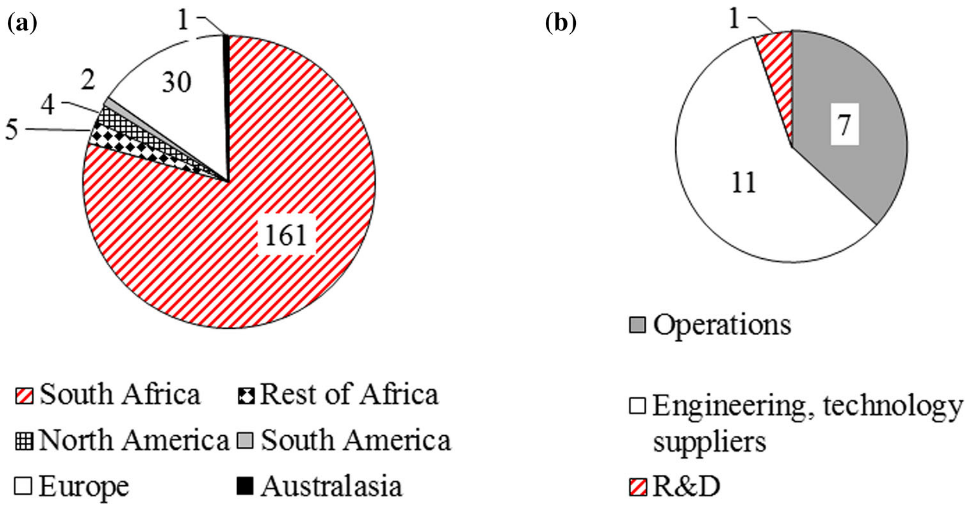

Fig. 1. (a) Distribution of the 203 delegates that attended the 1st Furnace Tapping Conference hosted by the SAIMM, between regions. (b) Distribution of the first authors of the 19 papers, published in the proceedings, between fields.[2]

hole is maintained at regular intervals. Examples of tap-hole maintenance practices include rebuilding the tap-hole channel by using reconstructive clay[8] and cleaning the tapblock at the cold face, or even replacing a thin refractory brick[9] forming the interface between the tapblock and the mudgun. Tap-hole repairs are typically large maintenance activities, and can be either planned or unplanned events. Planned tap-hole repairs can range from only a few sections of the tapblock being replaced, taking a few hours to complete,[10] to a large section of the sidewall—including the tapblock—being replaced, taking several weeks.[10,11] Unplanned tap-hole repairs typically take place after an uncontrolled event in which a tap-hole failed to close, or a tap-hole burn-though occurred.[10] The amount of repair work required depends on the extent of the damage.

In the following sections the criteria required to address each aspect of the tap-hole life cycle during the design phase are discussed in more detail. A submerged arc furnace (SAF) producing silico-manganese (SiMn) is used to contextualise the discussion.

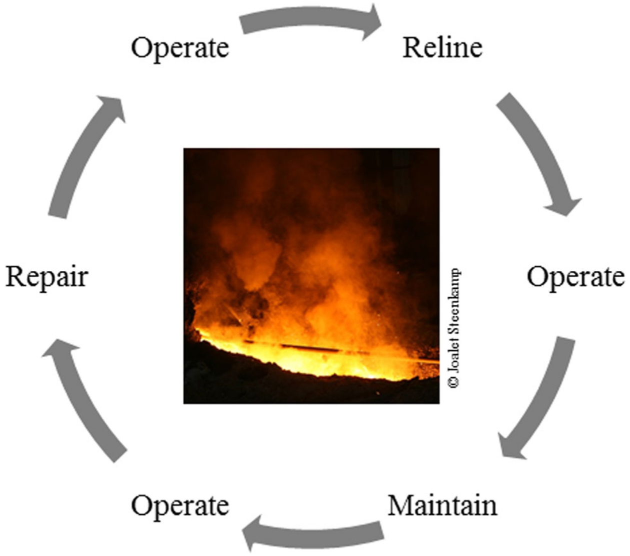

Fig. 2. The tap-hole life cycle. The tapping launder taken at one of the single-level tap-holes at Transalloys' silicomanganese smelter.

SiMn Production in SAF

In South Africa, SiMn is produced by the carbothermic reduction of manganese ore and quartz in submerged arc furnaces (SAFs). Typically, the manganese ore utilized contains (by mass) 37.0% Mn, 5.7% Fe, 2.8% MgO, 0.3% Al_2O_3, 5.9% SiO_2, and 11.9%CaO. As indicated in Fig. 3, the manganese ore, carbonaceous reductant (typically bituminous coal and coke) and quartz are fed through feedports in the roof, which is suspended above the furnace. The Söderberg electrodes (1.6 m in diameter on a 48-MVA furnace) provide the electrical energy required to sustain the endothermic reduction reactions and are submerged in a gas-permeable burden. The Söderberg electrodes are typically in contact with a coke-bed which consists of liquid slag and carbonaceous particles. Partial reduction of the ore occurs in the burden and final reduction in the coke-bed. The liquid alloy formed collects at the bottom of the furnace. The process containment system typically[12] consists of a water-cooled steel shell, lined with a fireclay brick back-lining, and carbon paste working lining, which is rammed in position. The tapblock is typically manufactured from silicon-carbide (SiC). The process off-gas that forms leaves the furnace through the burden, and is collected by a gas extraction system, the off-gas ports for which are located in the furnace roof. Liquid alloy and slag is tapped through single-level tap-holes, typically at 4-h intervals. The duration of

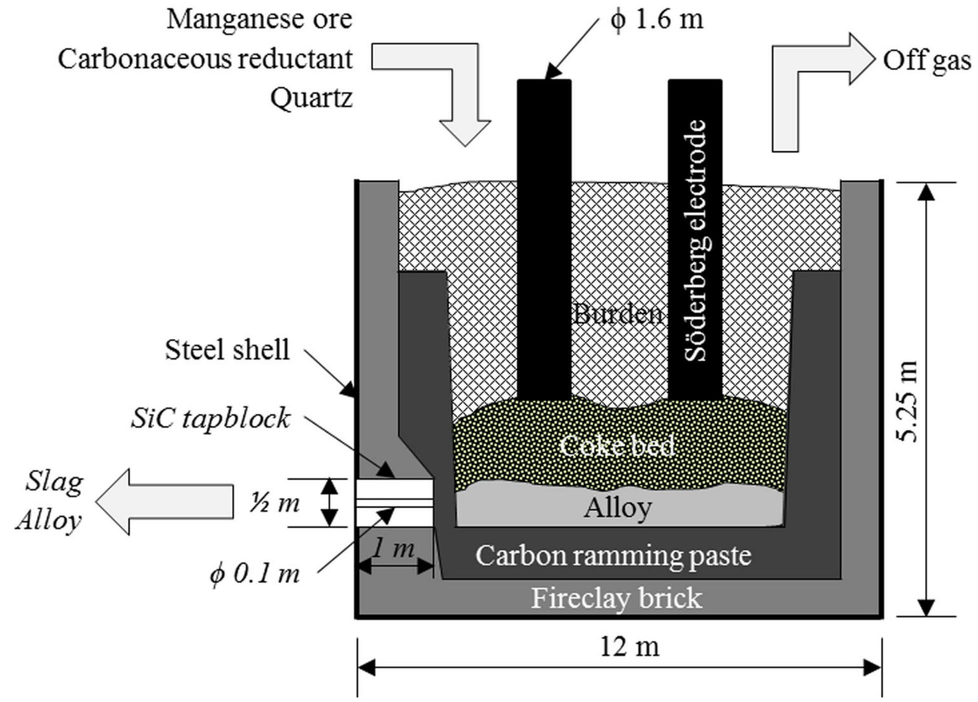

Fig. 3. Conceptual layout of a 48-MVA submerged arc furnace producing silicomanganese. Aspects related to tapping, are indicated in italics.

a tap is typically 35 min, and sizes of taps range between 30 tons and 50 tons (slag and metal). Both liquid and solid state separation of slag from metal occurs downstream. The process conditions for a 48-MVA furnace are summarised in Table I.

Design to Reline

In many ways, designing for tap-hole installation during a total reline is the easiest part of the design process, as the refractory lining is built from scratch, the furnace is accessible, and all work is done at room temperature. Criteria to consider when relining the furnace include:

1. The order of installation (and installation methods) of tap-hole system components, including lintels, copper cooling elements, temperature monitoring equipment, tapblock or components thereof, and the refractory mortar used to form liquid-proof seals between components.
2. How to position large, heavy components such as tapblocks and copper cooling elements.
3. How to position sacrificial start-up thermocouples, if fed through the tap-hole, and plug the tap-hole prior to start-up.

Design to Operate

Normal Operating Conditions

When designing for operations, both normal conditions and emergency conditions should be taken into account. Criteria to consider for normal operations include:

1. Compatibility between process streams (alloy or matte, and/or slag), and refractory materials (including tap-hole clays), at tapping conditions.
2. Whether or not to include cooling elements such as water-cooled copper blocks in the tap-hole design.
3. Whether a single level or bi-level tapping practice will be followed, and where to position the tap-holes in terms of this practice.
4. The number of tap-holes to install on a specific level, which depends on the tapping practice, operating philosophy, and management of expected wear.
5. Where to position the tap-holes around the circumference of the furnace, which depends both on the post-tap-hole operations as well as wear patterns expected in the furnace.
6. How to link the material stream flowing from the tap-hole with the post-tap-hole operations.
7. How to open and close the tap-hole. If a drill-and-mudgun is used, where to position and how to support it, whether it should have a hydraulic or pneumatic power-pack, and whether or not any instrumentation is required. It is also important to decide what types of tap-hole clays to use, and how to store and prepare the clays prior to use.
8. Where to install secondary fume extraction units, to ensure that the fumes generated during tapping are removed effectively and expediently from the tapfloor.

Tap-hole refractories are subjected to considerable erosive attack as well as physical damage as a result of the opening and closing of the tap-hole. The tap-

Table I. Process conditions for a 48-MVA SAF producing SiMn in South Africa (where applicable, daily averages with standard deviation, calculated for production data for 2014)

	Unit	Average	Standard deviation
Ore	Metric tons/day	334	43
Coal	Metric tons/day	224	20
Coke	Metric tons/day	20	10
Quartz	Metric tons/day	99	15
SiMn alloy	Metric tons/day	160	20
Slag	Metric tons/day	160	6
Slag/metal ratio	–	1.0	–
Power consumption	MWh/ton alloy	4.0	0.3
Slag tap temperature	Kelvin	1923[a]	–
Metal tap temperature	Kelvin	1823[a]	–
SiMn alloy composition			
Mn	% by mass	66.4	1.3
C	% by mass	1.8	0.2
Si	% by mass	16.3	0.6
Fe	% by mass	14.7	0.9
Total	% by mass	99.2	–
Slag composition			
MnO	% by mass	12.9	1.7
SiO_2	% by mass	46.3	1.5
MgO	% by mass	5.7	0.7
CaO	% by mass	25.0	1.6
FeO	% by mass	0.3	0.02
Al_2O_3	% by mass	4.7	0.6
Total	% by mass	94.9	–

[a] Estimated.

hole refractories require regular replacement, and it is therefore common practice to use the best grade refractories possible in an attempt to maximize tap-hole life and minimize the furnace downtime required for tap-hole repairs. Different refractories display different characteristics such as thermal conductivity, linear expansion, crushing strength, service temperature, etc. The selection of which tap-hole refractories to use is often a trade-off between the different characteristics, chemical compatibility with the process, and economic factors. At SiMn smelters in South Africa, the selection of tap-hole refractory material has historically been based on industrial experience. Experimental and modeling work done in recent years[12–15] has enhanced the understanding of the potential for chemical wear, and offered ways to evaluate different types of refractory materials via desktop and laboratory-scale studies (see also discussion on the role of modeling below).

Water-cooled copper tapping blocks are very common on furnaces in non-ferrous operations, and substantially increase tap-hole life in these industries.[3] During the design stage, finite element analysis (FEA) modeling is undertaken to determine the type and intensity of cooling required in the tap-hole based on the particular process conditions envisaged, e.g. tapping temperatures. Usually, the major difference between tapblock designs is whether they are shallow- or deep-cooled, which is determined by the cooling intensity required during a tapping event. The modeling also assists in indicating the best positions for the installation of temperature measuring devices (both thermocouples as well as resistance temperature detectors) to enable tap-hole temperature and heat flux monitoring to be undertaken during operation. The design further needs to take into account the type of cooling water pipe design to be used. Two types of piping commonly used are: cast-in Monel piping or drilled piping, each with their own advantages and disadvantages. The incorporation of a face-plate into the design (either water-cooled or non-water-cooled) is common practice to protect the tapblock from drilling and lancing errors as well as providing a flat face for the mudgun to bear against.

The main advantage of having a bi-level tapping arrangement is that the bulk of the separation between metal and slag occurs in the furnace, reducing the need for downstream separation processes (and associated costs). South African producers of SiMn prefer single-level tap-holes to bi-level tap-holes, as the nature of their process makes operating a tap-hole dedicated to tapping slag very difficult to manage, and downstream processes to separate metal from slag are already in place.

In operations where tap-hole wear and the resulting maintenance can have a major impact on furnace throughput, such as the furnaces used in the platinum industry, design of the furnace with two or preferably three metal/matte tap-holes is preferable. One can then cycle maintenance on the three tap-holes in a planned, systematic manner, which limits the overall downtime experienced by the furnace due to tap-hole issues and thus maintains furnace throughput at optimum levels. A similar practice is followed by South African producers of SiMn: each furnace has two tap-holes to allow for redundancy—if a small repair is required on one tap-hole, the furnace can still be tapped through the other—and distribution of wear is effected as the tap-hole is one of the two high-wear areas in the furnace.

The use of a mudgun and drill can have a major impact on tap-hole life and, although expensive, are generally a worthwhile investment in both tap-hole operation and the safety of operating personnel, as they reduce the time spent in the immediate vicinity of the tap-hole. If a mudgun/drill unit is installed, the maintenance thereof is of prime importance and should include at least daily alignment tests to ensure drilling is not off-center or angled to one side. Also, the maintenance of emergency equipment such as nitrogen accumulators for use in the case of power failures becomes critical. It is also preferable to install two units per furnace each of which can access all tap-holes, for redundancy.

Drilling reduces the amount of lancing required for tap-hole opening, which is a major cause of wear in the tapping channel.[16] The installation of lance guides is also critical to ensure that tapfloor personnel are able to maintain the lance straight in line with the tapping channel and not lance into the tap-hole refractories. The design of the lance guide should be such that it can be moved out the way once the tap-hole is open, while ensuring that alignment is not compromised. Some operations prefer to just drill the tap-hole open and dispense with lancing altogether, and absorb the increased consumption of drills into the operating cost. Although more costly, this approach reduces tapping channel wear and increases personnel safety.

Optimal performance of tap-hole plugging has a major impact on tap-hole life. The use of the correct amount of clay is important to ensure that the tapping channel is completely cleared of metal/slag and replaced with clay. Use of excess clay can result in clay being pushed past the hot face into the molten bath, which can result in boiling and concomitant refractory wear on the hot face of the tap-hole and the surrounding sidewall refractories above the tap-hole. Too little clay results in incomplete filling of the tapping channel. This can often happen if there is poor mating of the mudgun with the cold face of the tap-hole during plugging, with clay being extruded into the launder and not penetrating the tap-hole channel. Incomplete filling of the tap-hole during plugging will require lancing at the next tap, as the drill can only drill through clay and not frozen process material. Maintenance of the cold face of the tap-hole is critical to ensure that the mudgun is flush with the cold face. In addition, sacrificial plates of compressible fiber board are often installed on the end of the mudgun to ensure optimal mudgun/tap-hole interfacing, and prevent loss of clay.

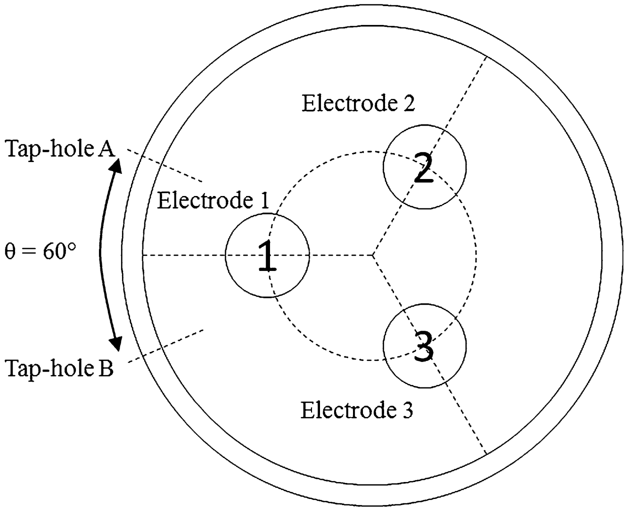

Fig. 4. Conceptual layout of the two single-level tap-holes, and the three Söderberg electrodes, in a submerged arc furnace producing silicomanganese. Electrode 1 is referred to as the tap electrode.

The preferred way to open and close tap-holes at SiMn smelters is by means of a hydraulic drill-and-mudgun, positioned on a pedestal. As slag and metal are tapped into ladles which are transferred by overhead cranes, the two tap-holes are positioned 60° apart (see Fig. 4) on the side of the furnace facing the furnace bay. The furnace bay is where the post-tap-hole processing of liquid material occurs. For SAFs producing SiMn, equilateral positioning of the two tap-holes to either side of one of the three electrodes (referred to as the tap electrode; see Electrode 1 in Fig. 4), improves conditions for tapping. The liquid zone in the SAF is clover-shaped around the three electrodes. To maximize the opportunity for metal and slag to remain fluid during tapping, the tap-hole should be positioned in the middle of one of the leaves of the clover, ensuring the shortest distance between the liquid zone and sidewall. To manage risks from both a tap-hole wear and tap-hole maintenance perspective, more than one tap-hole is installed. To address both the fluidity and redundancy requirements, the tap-holes are typically installed 60° apart, equilateral to the centerline of the tap-electrode.

Role of Modeling

Advances in computational technologies have made available modeling techniques that can be applied during the design stage in order to optimize the tap-hole design. Modeling techniques allow for studies in which the effects of variations in design and operating parameters unlikely to be tested on an actual furnace are evaluated. The following physical phenomena can be represented by theoretical models, which are of interest during the design stage:

- *Heat transfer* The amount of thermal energy removed through the cooling system and temperature distribution variation in the refractories are determined by the temperatures of materials on the refractory cold- and hotfaces, the geometry of the tap-hole refractory, refractory thermal conductivity and heat capacity, and the strength of bonds between the refractories and cooling system, expressed as contact resistances.
- *Fluid flow* During tapping, viscous fluids flow from the slag and metal baths, through porous zones and out of the tap-hole. The mass flow behavior of the tap stream in terms of tapping rate, and the tapped amounts of the respective materials, depends on the physical properties of the fluids (viscosity, density), the permeability of the tap-hole and porous zones, and the pressure difference over the porous zones and the tap-hole. The internal fluid pressure is approximated as consisting of the fluid hydrostatic pressure, burden pressure, and the crater pressure of gases around the electrodes.
- *Chemical refractory wear* Chemical wear of the refractory occurs mostly due to chemical reaction with the slag and metal, or the dissolution of refractory components into the slag or metal. The potential (and rate) of wear is determined by the activity of the reaction products and dissolved components in the slag and metal at the relevant temperature.

Some modeling approaches applicable to the simulation of the relevant tapping process aspects are:

- *Physical models* Experiments can be set up in which a refractory material is in contact with slag and/or metal at relevant temperatures in order to test material compatibility by obtaining an indication of the amount of expected wear, and to analyze possible reaction products.[14,17] Fluid flow during the tapping process can also be simulated with physical models [16]; however, these often have limited applicability due to the reduced scale and incomplete matching of process parameters which can be achieved in a laboratory.
- *Mathematical and computational fluid flow and heat transfer models* An analytical modeling approach can simulate fluid flow by solving pressure drop equations for fluid flow through the porous zones in the furnace and the tap-hole.[18] The tap-hole domain and tapping process can be modeled in greater detail, and extended to two or three dimensions, using computation fluid dynamics (CFD) modeling in which fluid flow and heat transfer is solved simultaneously. A commonly used method for numerical/computational models is the finite volume method, in which the domain is divided into cells/elements and numerical solutions to the governing equations are obtained within the cells/elements, while appropriate boundary conditions are applied at the perimeter of the region. CFD modeling results may be obtained for steady-state or transient conditions, and may include temperature distributions and variations to expect in operation, and heat removal rate as a function of tapping rates and amounts of slag tapped. An example of the application of a model based on CFD to evaluate aspects of tapping is discussed for silicon producing furnaces.[19]
- *Thermodynamic chemical wear modeling* Thermodynamic modeling can be applied to estimate the amount of chemical refractory wear from contact with slag or metal, by evaluation of the potential for wear due to chemical reaction or dissolution. Thermodynamic properties can be calculated, such as the activities of components in the slag or metal and chemical equilibrium. This method may also be used to indicate operational constraints, such as slag chemistry compositions which ensure compatibility with a chosen refractory material.

The application of thermodynamic modeling using FactSage software to evaluate slag–refractory interaction in a SiMn-producing furnace is reported in the literature.[14,15] The potential for metal to cause refractory wear was evaluated by calculating activities of solid graphite and SiC for typical Si-Mn-Fe-C metal compositions at temperatures of 1823–1873 K, where activities of <1 indicate it not to be saturated in that component and wear of a SiC or carbon-based refractory, respectively, could occur. Chemical attack of a carbon-based refractory by slag was also evaluated considering the SiO_2 reduction reaction forming SiC, with wear likely to occur when the calculated activity of SiO_2 (reference state cristobalite) in the slag is higher than the equilibrium activity (e.g. 0.17 at 1873 K).[20]

- *Physicochemical property models* Models exist to estimate slag and metal physical and thermochemical properties as used in the mathematical fluid flow and heat transfer models. This step may include thermodynamic modeling in which the amount of precipitated solids in the slag is estimated at chemical equilibrium, which would then be used in the calculation of the properties themselves. Examples of modeling of the properties of manganese-bearing slags have been discussed,[21] and the application thereof in analytical tapping flow modeling.[18]

The following are important to improve the accuracy of modeling tap-hole and tapping aspects:

- The model domain and phenomena modeled should include all important aspects that can influence the tap-hole performance and overall process performance influenced by tapping, including variation of any aspect during the operation stage of the tap-hole life cycle (e.g., domain changes due to refractory wear or solidified accretions).
- Transient modeling should be considered in addition to steady-state modeling, to identify expected variations in process variables that could be used for condition monitoring during operation to indicate possible excursions away from design conditions.
- Boundary conditions should be specified as typical values based on operating experience, or modeled as functions of other available process variables.
- Models should be evaluated for different process conditions (e.g., temperature, chemical compositions), allowing for an expected degree of deviation from normal operating conditions. This approach may also be used to determine tap-hole failure limits and relate these back to instrumentation and monitoring measurements (see next section on emergency conditions).
- Physicochemical properties of refractories, and of the slag and metal fluids (including viscosity, thermal conductivity, density, heat capacity), should ideally be included as sub-models of temperature and chemical composition,[21] as opposed to assuming constant values. Allowance should also be made for the inclusion of variable amounts of precipitated solids, estimated with thermodynamic equilibrium calculations.
- Different datasets should be considered for thermodynamic modeling, and the results compared, since it has a direct effect on the accuracy of the results, but is often difficult to validate.
- Where possible, models should be validated against plant data by comparing results with operational data. In this case, plant data should be critically evaluated and corrected where necessary (e.g.,slag chemical compositions reflecting entrained metal.[18])

Emergency Conditions

Another important aspect often overlooked during the design phase is the design of tap-holes for emergency conditions. During the design phase, the assumption should be made that it is possible that the tap-hole will fail and the furnace will run out at some stage during its life. The main goal is to limit the damage to people and property that can result from a tap-hole run-out. Criteria to consider for emergency conditions include:

1. Whether or not to install a dedicated tap-hole to utilize in emergency conditions.
2. When the tap-hole fails and the furnace runs out, consider where the liquid material will flow, and what equipment will be destroyed. The area under the tapping platform and in the aisle should be designed such that the metal and slag will be directed away from the furnace during a run-out. This includes sloping of floors, protecting support structures with refractories, and channelling any run-out away from any equipment in the furnace aisle.
3. The natural flow of liquid slag and metal should be away from the furnace into areas where no water will be present, to limit the risk of explosions. Similarly, instrumentation wiring and areas where personnel are working should be avoided. Water-pipe and cable racks, control rooms, and the control systems for the tapping equipment, should all therefore be positioned away from the natural flow of liquid slag and metal.
4. Positioning of major structural support beams should be considered carefully. These beams should remain intact at all times, and therefore be positioned away from the path of liquid material flow. This could result in the need for (sacrificial) auxiliary support beams.
5. Not only the layout of the tapfloor but also areas below the tapfloor should be taken into account.
6. Not only the effect of contact with liquid metal and slag but also the effect of thermal radiation from these streams should be taken into account.
7. Ideally, the mudgun should be available at all times, even in emergency conditions, to close the tap-hole, and, if damaged, be rectified or replaced in a short space of time, to allow for the normal opening and closing practices to be resumed once the tap-hole has been repaired. Installation of the equipment on a concrete plinth, rather than steel, increases the probability of the mudgun surviving a run-out event.
8. The furnace aisle should be kept clear of support equipment such as ladle heaters. Sometimes, these are installed at the end of the launder and, if there is a run-out, the equipment will be damaged.
9. If fuel lines are present, this could result in a fire causing further consequential damage.

Design to Maintain

When managing the tap-hole life cycle, the age-old adage applies: *The best way to get out of trouble, is to stay out of trouble*. This implies that preventative maintenance of the tap-hole is of utmost importance. In this section, small maintenance aspects (executed in <2 h) are addressed. In the next section, criteria for maintenance activities executed in more than 2 h are addressed. Criteria to consider for tap-hole maintenance during the design phase include:

1. Understanding the tap-hole maintenance strategy to be followed during furnace operation. These strategies are usually either Time-Based Maintenance, or Condition-Based Maintenance. If the latter strategy is to be used, the tap-hole and surrounds need to be fitted with sufficient instrumentation such that the condition of the tap-hole can be adequately monitored.
2. The installation of thermocouples (or other temperature measuring devices[22,23]) in the vicinity of the tap-hole can be very beneficial in terms of giving prior warning of tap-hole problems, and can be used to monitor tap-hole refractory performance and to initiate a tap-hole repair. Placement of these instruments needs to be considered in the design phase, to ensure that they are not exposed during tapping, by installing splash guards and insulation panels. They also need to be accessible to maintenance personnel for ease of replacement.
3. When operators utilize the drill depth as an indicator of tap-hole condition, the drill-and-mudgun should also be instrumented as such.

At SiMn smelters in South Africa, the tapblock condition is typically monitored in four ways:

(a) By monitoring the shell temperature, by using thermocouples as well as thermographic images of the shell.[12]
(b) By monitoring the flow pattern of liquid alloy and slag during tapping.
(c) By monitoring the drill depth.
(d) By monitoring the clay consumption.

Ideally, shell temperatures should be <573 K. Shell temperatures of the order of 773 K will warrant further investigation. High shell temperatures are attributed to either an air-gap between the steel shell and refractory, or decrease in refractory thickness, due to wear. To determine if the former is the case, an inspection hole is drilled into the steel shell and if, upon inspection, it is found that the air-gap exists, used to fill the air-gap with a two-part carbonaceous heat-setting cement to re-establish contact between the steel shell and refractory. If no air-gap is found, then it is concluded that the increase in shell temperature is due to a decrease in refractory thickness, triggering a tap-hole repair, or total reline.

Both turbulent flow of the tapping stream and short drill depths are indicators of a worn tapping channel. To repair the tapping channel, a hole is drilled three-quarters into the tap-hole using a large-diameter drill-bit, and subsequently filled with a high-quality, low-viscosity clay, using the mudgun. The mudgun is kept in place, long enough to allow for the low-viscosity clay to fill any cracks in the tapblock. Tapping operations are then resumed using a drill-bit with normal diameter.

Clay consumption may be monitored daily, and high clay consumption may indicate excessive wear on the interface between the mudgun and tapblock.

Design to Repair

As with the smaller preventative maintenance practices discussed in the previous section, planned outages for large maintenance activities are better than emergency repairs, since larger-scale repairs often require materials and equipment not readily available on site. Criteria to consider for tap-hole repairs during the design phase include:

1. Designing tap-holes with multiple separate brick modules instead of a single tap-hole brick such that a number of minor repairs (such as 1, 2 or 3 modules) can be conducted to extend overall tap-hole life cycle, and reduce the number of deep repairs (such as the 5th or 6th module) that need to be conducted. These minor repairs usually do not require downtime and the furnace can continue operating using another tap-hole, whereas deep repairs often require the furnace to be drained and operated at low power to ensure the safety of maintenance personnel and prevent the possibility of a furnace run-out.
2. The interface between the brick modules and the sidewall lining needs to be considered. For instance, if the furnace hearth/sidewall interface is a skew-back, integrating the tap-hole brick modules into the skew-back makes deep tap-hole repairs extremely difficult (and sometimes impossible), and can result in extended furnace downtime.
3. Access to the tap-hole for personnel, materials, and equipment during maintenance and repair can have an impact on the time taken for tap-hole repairs. If, for example, the tap-hole is constructed with doghouse copper coolers, installation of a support beam for rigging in the coolers is useful, and can also be used for jack hammer support. The design of the water piping supplying the tap-hole coolers should be such that it is easily accessible and removable without excessive spillage during any maintenance on the tap-hole.

At SiMn smelters in South Africa, tapblock repairs are conducted once the furnace is tapped empty (but not melted down). The worn tapblock, and surrounding refractory bricks if necessary, are removed mechanically. During the breakout, the furnace contents will be hot, and therefore continue to tap. As this is expected, the area around the furnace tapfloor is prepared by ensuring that it is dry, and that the floor is covered with a layer of crushed slag, to contain the liquid alloy and slag.

An ideal tapblock repair consists of a single tapblock, installed in brick lining that tapers to the back, where only the tapblock has worn and needs to be removed, whilst the brick lining maintains the integrity of the sidewall. The replacement block is covered with refractory cement and positioned using the mudgun.

In a non-ideal tapblock repair, both tapblock and surrounding refractory have worn, and need to be replaced. A section is cut from the steel shell to access the worn refractory, and upper sidewalls supported with temporary steel supports, before the tapblock and worn bricks are removed. The tap-hole is then rebuilt from the bottom up. Refractory lining life is typically from 6 to 10 years, with at least one major tap-hole repair included.

CONCLUSION

The management and design of furnace tap-holes are both of interest and a challenge to furnace operators. During the design phase, it is important to address all aspects related to the life cycle of the tap-hole, including maintenance and repair activities as well as normal and emergency operations.

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