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Furnace integrity of ferro-alloy furnaces – symbiosis of process, cooling, refractory lining, and furnace design

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Abstract – The integrity of a furnace ensures a reliable and safe furnace operation as well as a long furnace campaign life. Process and operational practice know-how, expertise in refractory and furnace cooling, as well as furnace design, are the key factors for increased furnace integrity.

A complete understanding of the process is most essential for designing reliable and efficient metallurgical plants, in particular for electric furnaces and other pyrometallurgical furnaces, as applied in the ferro-alloy industry. It allows the correct dimensioning of pyrometallurgical vessels. Furthermore, it provides the fundamental data and information for all related auxiliaries and surrounding units such as the off-gas system, raw material and product handling, cooling systems, *etc*.

Refractories have a major influence on the opex, and therefore the profitability, of any smelting plant. The initial refractory material cost is significant, but the 'full life value', including loss of production and unexpected failures, can be even more significant. The correct understanding and definition of the process is most important to provide an optimized lining concept. Achieving the best 'whole of life value' requires a fully integrated management system.

In most metallurgical vessels, the lining wear is controlled by an additional cooling method in certain areas of the furnace. Over the past decades, PolyMet Solutions, SMS, and Mettop developed numerous cooling systems for almost all pyrometallurgical processes in the ferrous, non-ferrous, and iron and steel industries. Intelligent solutions are required in highly stressed areas, for example, locations facing abrasion by the off-gas or bath turbulence, tap-hole areas, aggressive slag, changing slag compositions, thermal cycling, or high-temperature/superheat levels. This paper provides an overview of our solutions in furnace integrity optimization.

Keywords: electric furnaces, refractory, cooling, ILTEC, ionic liquid, process, furnace integrity, furnace lifetime, submerged arc furnaces

INTRODUCTION

During the past years, almost all metal prices have been under pressure, and, therefore, competitive solutions are becoming important to maintain a stable market position. Such situations also bear opportunities for companies in the ferro-alloy metals business.

SMS group in Germany, including Metix in South Africa, supplies complete concepts in the ferro-alloy industry. As far back as 1906, the SMS group delivered the first submerged arc furnaces. Meanwhile – over the past 100 years – SMS supplied more than 750 submerged arc furnaces and major components to our customers worldwide, who operate plants for the production of ferro-alloys, Si-metal, non-ferrous metals, and other applications. The smelter departments of the SMS group in Düsseldorf, Germany and Johannesburg, South Africa have worked out numerous solutions to ensure the profitability of the operating industry in the ferro-alloy business (Degel *et al.*, 2011a). Many highly interesting and challenging furnace projects are being implemented, including the world's largest FeNi furnace for POSCO SNNC, South Korea, the FeCr production line based on DC technology working with an innovative, building-suspended electrode column for JSC Kazchrome, the first FeMn/SiMn plant equipped with a hybrid gas-cleaning system (scrubber system – wet ESP combination) for Sakura, Malaysia, an innovative smelter for fused magnesia production for Satka, as well as a complete silicon plant for PCC in Iceland, which will be commissioned soon.

In 2016, SMS group GmbH and Mettop GmbH in Austria founded a joint venture – PolyMet Solutions GmbH in Austria – serving producers mainly in the non-ferrous metals industry, with the target to develop new innovative and especially profitable solutions for the metals producing industry (Filzwieser *et al.*, 2016). It mainly includes the primary pyrometallurgical process routes, where metals are processed out of ore/concentrates. This is in contrast to the secondary routes where mainly metals are processed out of secondary metal sources. With the joint venture between Mettop and SMS engineering complete, process routes including the overall design of refractory concepts in 3D, engineering, equipment and refractory supply, and commissioning of the plant are targeted. Covering all systems from the raw materials and smelting metallurgy, through shaping, and up to the finishing.

Table 1: Product portfolio of PolyMet Solutions

<table>
<tr><th>Primary production</th><th>Secondary production</th><th>PolyMet Solutions fields of expertise</th></tr>
<tr><td colspan="2">Copper, nickel</td><td rowspan="6">- Strong process competencies in primary concentrate smelting with PolySmelt
- Improved solutions for conventional primary smelters
- PolyConvert for efficient conversion to blister copper
- PolyRefine optimized vessel
- Accurate anode casting technology
- Advanced tankhouse technology by Mettop
- 3D refractory engineering
- Refractory lining and quality concept
- Refractory supply
- Furnace integrity
- Plant and furnace engineering and supply by SMS
- Execution competencies of SMS
- Advanced components by Mettop
- Slag and metal granulation systems
- Gas cleaning plants
- Auxiliaries
- Turnkey competencies
- Supervision and seminars</td></tr>
<tr><td>- Flash furnace
- TSL reactor
- Teniente/ Noranda reactor
- Kivcet reactor
- Mitsubishi process
- PS converter
- EAF
- Vanyukov
- SKS</td><td>- Shaft furnace
- TBRC
- Reverberatory furnace
- PS converter
- Short rotary furnace
- TSL reactor</td></tr>
<tr><td colspan="2">Lead, zinc, tin</td></tr>
<tr><td>- TBRC
- TSL reactor
- Shaft furnace
- Kivcet reactor
- Vanyukov
- Teniente
- QSL</td><td>- TBRC
- TSL reactor
- Shaft furnace
- Kaldo
- Reverberatory furnace
- Short rotary furnace
- OBBF (oxygen bottom blow furnace)</td></tr>
<tr><td colspan="2">Precious metals</td></tr>
<tr><td>- 6-inline and circular electric furnace
- PS converter
- TBRC</td><td>- PS converter
- TBRC
- TSL
- Plasma furnace</td></tr>
</table>

FURNACE INTEGRITY

The rising demand to operate metallurgical plants in a cost saving mode is becoming increasingly difficult and therefore warrants optimized processes and tailor-made solutions. Solutions that improve refractory lifetime and thus furnace availability are essential to the commercial success of any operation or process concept.

Our approach for improving and optimizing metallurgical processes is seeing the entire process as a whole. A combined consideration of metallurgical reactions, process, furnace geometry, steel construction, and refractory quality and lining concept, leads to an improved life-cycle value.

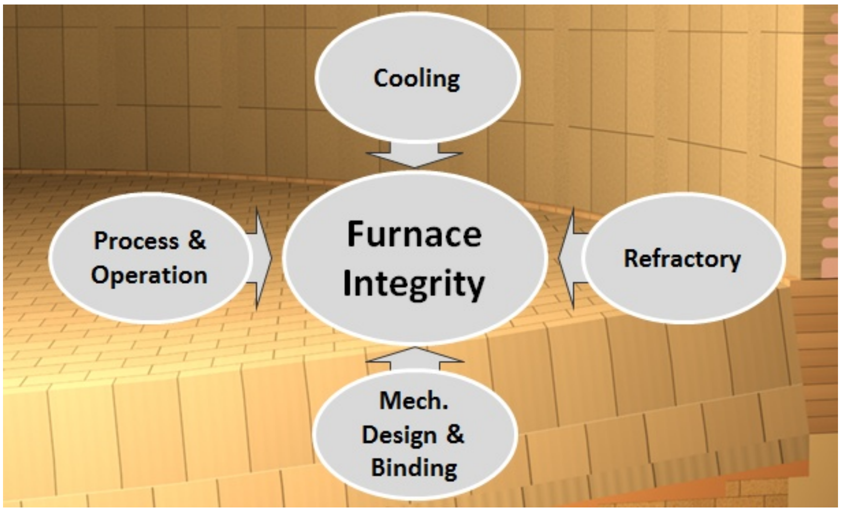


Figure 1: Definition of furnace integrity

The applied 3D construction method, CFD modelling, as well as process modelling, enables a perfect synergy of refractory design and arrangement of cooling solutions.

The phrase 'furnace integrity' is associated with a consideration of the entire process for creating the optimum solution and the best possible performance. Each plant has individual process routes, aggregates, and facilities, meaning each solution is an individual and tailor-made approach to a problem.

The entire process chain is considered, starting from raw material input to the final product. Also, all boundary conditions, for example, the availability of reducing agents, electricity, space, environmental aspects (chrome 6+), and the legal situation, must be taken into account.

Once the process route is fixed and the furnace is defined, the operational mode (such as charging principle, energy input), flow, and temperature are taken into consideration, to generate data regarding the interaction of the steel shell, the refractory material quality and concept, and the metal to be processed.

3D engineering of the entire refractory lining leads to a supplier-independent material list, and, furthermore, with the knowledge of the refractory concept, a broad range of different cooling solutions can be considered.

PROCESS

A complete understanding of the process is most essential for designing reliable and efficient metallurgical plants. It allows the correct dimensioning of a pyrometallurgical furnace for new ferro-alloy metals plants. The correct process definitions will result in a more profitable plant mainly due to:

- Higher efficiency
- Lower energy consumption
- Higher productivity and yield
- Longer furnace campaign life

- Improved safety
- Lower maintenance and shutdown costs

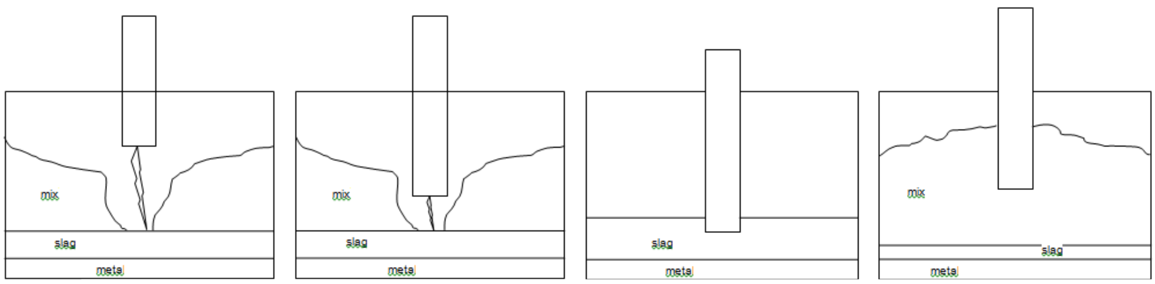
Furthermore, it provides the fundamental data and information for all related auxiliaries and surrounding units such as: the off-gas system, raw material and product handling, cooling systems, *etc*. It is also possible to integrate the models in the applied automation system for predictive operation of the unit.

General steps for the metallurgical evaluation
Prior to each project, our expert team generally follows the design steps shown below:

- Choice of raw materials and desired production rate (per hour) in intensive dialogue with customer
- Metallurgical calculation
- Choice of the applied technology, and kind of energy input
- Assumption of thermal losses
- Dimensioning of mechanical data
- Recalculation of thermal losses
- Calculation of electrical losses
- Dimensioning of electrical equipment
- Definition of nominal load
- Definition of guarantees

Of course, the described steps will change if the customer mentions special pre-conditions or constraints, for example, the consideration of special electrode diameters. In these cases, the conditions will be checked, discussed, and, if necessary, alternatives suggested (Degel *et al.*, 2007).

The choice of the raw material according to the customer's specifications has the biggest impact on the process. It affects the slag composition, and, on the other hand, the smelting pattern inside the furnace (based on the physical properties and the amount of energy input (see Figure 2).



open arc mode shielded arc resistance mode feeding mix resistance

Figure 2: Types of energy input according to the process (Degel *et al.*, 2007)

The physical properties determine whether the smelter can run in conventional resistance mode using the electrical resistance of the slag, shielded arc mode using the electrical resistance of the slag and arc, or using the electrical resistance of the feeding mix. Furnaces processing ores which yield a slag with a melting range below the liquidus temperature of the metal can never be operated in the shielded arc mode or with the electrodes penetrating the charged material only.

Optimized process – thermodynamic approach

Process modelling is possible for a single step up to a complex and whole facility, with numerous sub-processes. There is no restriction in achieving a sufficiently accurate model, assuming that the boundary conditions are known, enough data is available and the processing power for simultaneous calculations is available. By means of thermodynamic modelling, which is mainly based on a combination of the software HSC Chemistry and FactSage, together with empirical data, the optimum process can be identified. Every single process step is taken into account in order to obtain a holistic picture of the processing route.

The major benefit of an adequate process model is the possibility of running through a variety of situations in respect of:

- Raw material mixture, as well as point and time of addition
- Addition of slag forming agents, and slag composition, respectively
- Atmosphere and air/natural gas consumption, respectively
- Temperatures/heating load
- Composition of intermediate and final (main) products
- Internal circulation streams
- Change of the overall operational mode

Modelling entire process routes – optimized process

The example model presented in Figure 3 includes all vessels and process steps for a FeMn/SiMn facility. In the final setup, the model includes more than 150 elements and compounds, and allows automatic material and energy balancing.

This model is also capable of doing calculations when changing the operation mode from batch to continuous operation; hence, having a deep impact on the overall operational mode. This shows that an adequate model helps to design the facility in a way to provide major process and equipment changes with foresight.

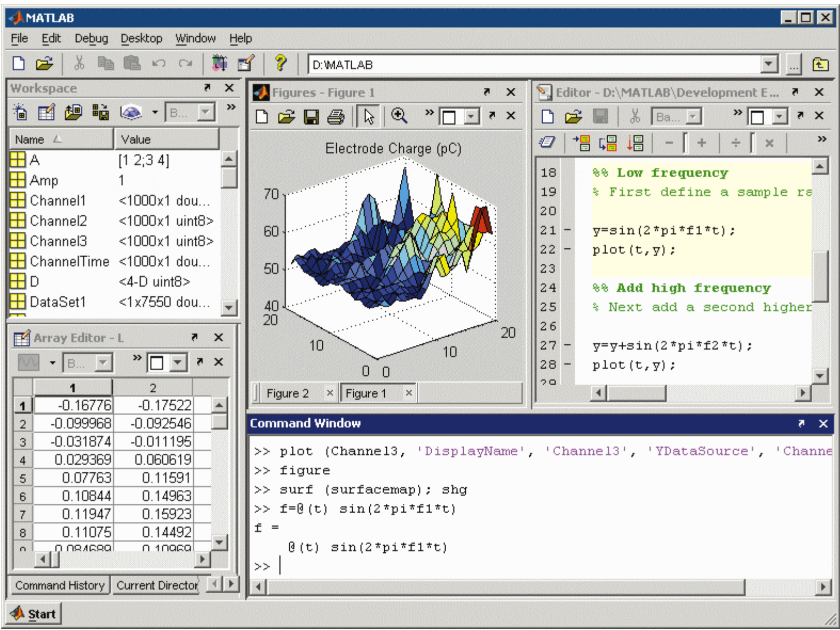


Figure 3: Modelling of FeMn/SiMn process (Degel *et al.*, 2011a)

Furnace optimization – CFD and thermal modelling

Once the type of furnace vessel is fixed, the geometries are known, and the refractory material is defined, investigations in terms of the heating load and temperature distribution can be conducted. A Computational Fluid Dynamics (CFD) model using geometry, temperature, and composition of the metal and slag, power and amount of energy sources is developed to provide an understanding of the temperature distribution, and to avoid refractory wear (Germershausen *et al.*, 2013).

Knowledge of the furnace geometry (steel construction, refractory thickness of each layer), combined with material data (refractory material, input material, temperatures of metal/slag), enables the thermal modelling of:

- Energy losses
- Temperature distribution within all layers
- Areas of increased temperature (hot spots)
- Expansion for the correct heat-up curve
- Cold spots for the prevention of hydration and corrosion

Furthermore, CFD modelling can be used for flow optimization of gaseous and liquid media. One example of a minor geometrical change with a high impact as a result of a CFD model is shown in Figure 4. In this case, the CFD modelling was used to find the optimum position for the feeding ports and the electrode columns, preventing build-ups in the off-gas systems (Van Niekerk, 2012).

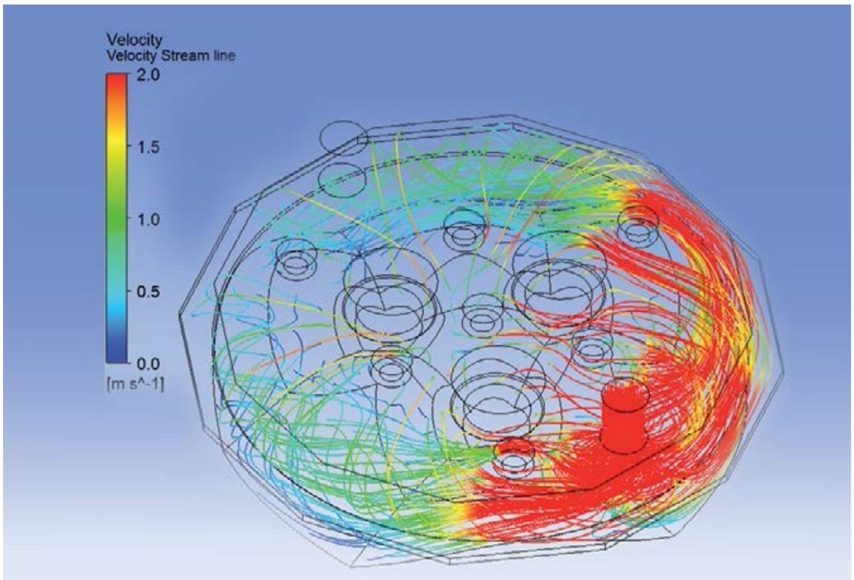


Figure 4: Off-gas flow pattern in an electric FeCr furnace

In general, a good understanding of the process, and an accurate control of the metallurgy have a great influence on furnace integrity. Taking the four DC furnaces at Kazchrome as a reference, the furnaces are using an 'insulating' lining without intensive sidewall cooling. The metal and slag temperature occasionally exceeds 1800°C. SMS managed, together with the client, to minimize the refractory wear only by disciplined process control (Degel *et al.*, 2011b).

MECHANICAL DESIGN AND BINDING

There are always controversial discussions about the correct dimensioning of binding systems. Generally, electric furnaces perform in the best way when they are permanently operating at design load. Each fluctuation in temperature leads to a certain thermal expansion or shrinking of the lining. This cannot be avoided and therefore certain processes require a mechanical lining binding system, which allows some flexibility in furnace operation. The SMS binding systems are working with tie rods allowing a permanently adjustable and controlled force from the shell onto the refractory lining (Degel *et al.*, 2012).

POSCO SNNC, as well as Eramet, operates such systems very successfully in their FeNi furnaces. This means that the end walls are designed to move with the expanding refractory during heat-up and during later operation. The rectangular copper slag-cleaning furnace, as operating for First Quantum Minerals in Zambia, is similarly designed.

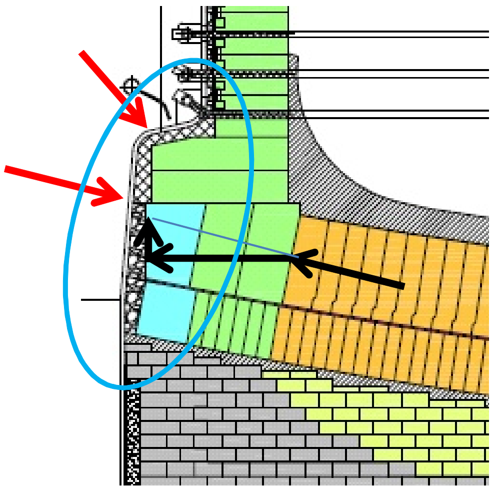


Figure 5: Cross-section of the sidewall cooling/binding system (Degel *et al.*, 2012)

COOLING

In most metallurgical vessels, the lining wear is controlled by an additional cooling method in certain areas of the furnace. Over the past decades, SMS and Mettop developed numerous cooling systems for almost all pyrometallurgical processes in the non-ferrous industry, as well as for the iron and steel industry (*e.g.*, for blast furnace tap-hole cooling, EAF steel shell cooling). Especially in highly stressed areas, *e.g.*, locations facing abrasion by the off-gas or bath turbulence, tap-hole areas, and areas subjected to aggressive slag, changing slag compositions, thermal cycling, or high temperature levels, intelligent solutions are required. There are various vessel cooling systems utilizing air cooling, spray cooling, or cooling with internal copper elements such as:

- Composite Furnace Modular (CFM) cooling solutions
- Copper staves for shaft furnaces
- Plate coolers
- Finger coolers
- Tailor-made systems

For example, the CFM cooling allows safe operation under extreme conditions, and can handle energy fluxes of > 400 kW/m^2, by using water or ionic liquid as a cooling medium. A panel can reach a height of > 2 m.

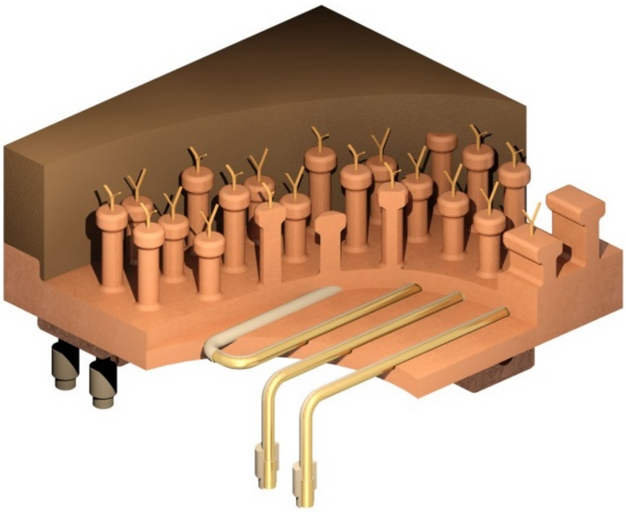


Figure 6: CFM cooling module

It is the increasing demand for an economic and cost saving operational mode that requires effective cooling in order to achieve low refractory wear and a good furnace lifetime, which is making cooling technology an important aspect of furnace operation. In some areas, it is necessary to apply cooling as an additional measure for increased furnace lifetime and optimization of the furnace performance. Therefore, as a result of the CFD models and from the know-how of the customer, a variety of different cooling solutions can be evaluated. Cooling of refractory is generally associated with the following advantages:

- Cooling of refractory is necessary for smelting operations to intensify their performance (higher power density)
- Better cooling of the refractory leads to a steeper temperature gradient within the brick lining (slow down wear)
- Steeper temperature gradient means less area for possible infiltration by liquid slag or metal
- Less infiltration leads to better performance of the refractory material (less wear)
- Better performance of refractory leads to increases in the campaign lifetime, cost savings, and more economical production

In Figure 7, an example of different options for cooling a side wall of an electric furnace is shown. The temperature distribution within the furnace wall for different water-cooled copper cooling elements indicates that different installation locations of plate coolers hardly influence the cooling effect inside the refractory lining. However, a high-intensity cooler with copper fingers and a castable refractory increases the energy flux, and the temperature gradient becomes steeper. Even more, with this kind of high-intensity cooling, it will be possible to create an accretion layer of solid material on the hot surface. This freeze lining concept can lead to an immense increase in furnace lifetime, as a solid frozen metal/slag layer will protect the refractory lining and there will be far less consumption of the refractory material under stable slag superheats and flow conditions.

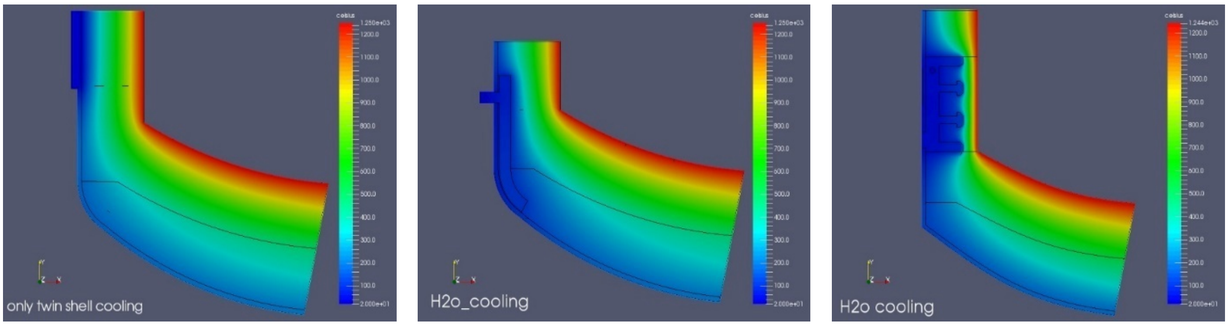


Figure 7: CFD Model of the temperature distribution, depending on different cooling solutions for the cooling of a furnace side wall: cooled plate at the outside of the steel shell (left), inside the steel shell (middle), and high intensity cooler (right)

In some applications, such as in silicon furnaces, the roof has to cope with extreme conditions. When blows occur, the gas stream shooting out of the burden can reach temperatures of up to 2500°C. The roof therefore faces extreme temperature fluctuations. In order to improve the integrity of the roof, we designed it with a channel-type cooling system (Kleinschmidt *et al.*, 2010). No welds are exposed on the hot underside of the roof, which minimizes the risk of potential water leaks.

To further reduce any operating risk resulting from water leaks, today furnaces are additionally equipped with a water leak detection system, which detects any small water leak. The roof also incorporates a Pitch Circle Diameter (PCD) adjustment system to change the electrodes' PCD. This improves the flexibility in terms of fluctuations in raw material characteristics. It also assists with optimization of process efficiencies following commissioning.

For optimal energy transfer, we developed a cast-in copper pipe into the coolers. The copper is cast over a cooled copper pipe to improve energy transfer, and prevent contamination which improves the recycling quality. Additionally, Metix holds a patent for adding small amounts of additives to the copper, in order to improve its recrystallization temperature as well as the strength. Furthermore, other material such as aluminium and steel are being tested.

ILTEC – A REVOLUTION IN FURNACE COOLING

SMS group and Mettop have signed an exclusive cooperation agreement for the utilization of an innovative cooling system based on an ionic liquid called ILTEC. This technology will improve the safety of metallurgical vessels greatly, and replace water with a non-explosive ionic liquid as a cooling medium in critical areas. This patented technology will be applied not only in the ferro-alloy and non-ferrous industry, but also for vessels and equipment in the iron and steel industry supplied by the SMS group.

The ILTEC Technology redefines plant safety (Filzwieser *et al.*, 2014). It comprises a closed loop cooling system, and the cooling medium IL-B2001, which was developed and patented by Mettop. But this doesn't mean that water as a coolant should be completely eliminated. Instead, the focus is on high-risk areas where explosions might occur. Our experts tested the liquid in steel plants, as well as copper plants, by injecting it below the liquid metal bath level. The successful outcome was a lack of rapid expansion or steam explosion or explosions, and only minor agitation in the liquid. That's a significant breakthrough in cooling technology. Furthermore, the flow-pattern characteristics are similar to that of water, which makes it easy to replace existing water cooling systems with ILTEC.

Figure 8: Hardware of ILTEC, as installed in Germany

REFRACTORY

Refractories have a major influence on the opex, and therefore the profitability of any smelting plant. The initial refractory material cost is significant, but the "full life value", including loss of production and unexpected failures, can be more significant. The correct understanding and definition of the process is most important in order to provide an optimized lining concept. Achieving the best "whole of life value" requires a fully integrated management system.

3D engineering of the furnace allows the automatic generation of a complete parts list of all bricks and additional parts (*e.g.*, steel plates, hanging hooks, expansion inserts), as all parts are named systematically, and are saved in a comprehensive list. Each brick format and every additional part is only drawn once and then copied, so that the parts list can be generated automatically and contains all the information required for the refractory lining installation, for example, required amounts of brick formats and qualities, number of expansion inserts, weight, volume, and positioning of bricks in different furnace areas.

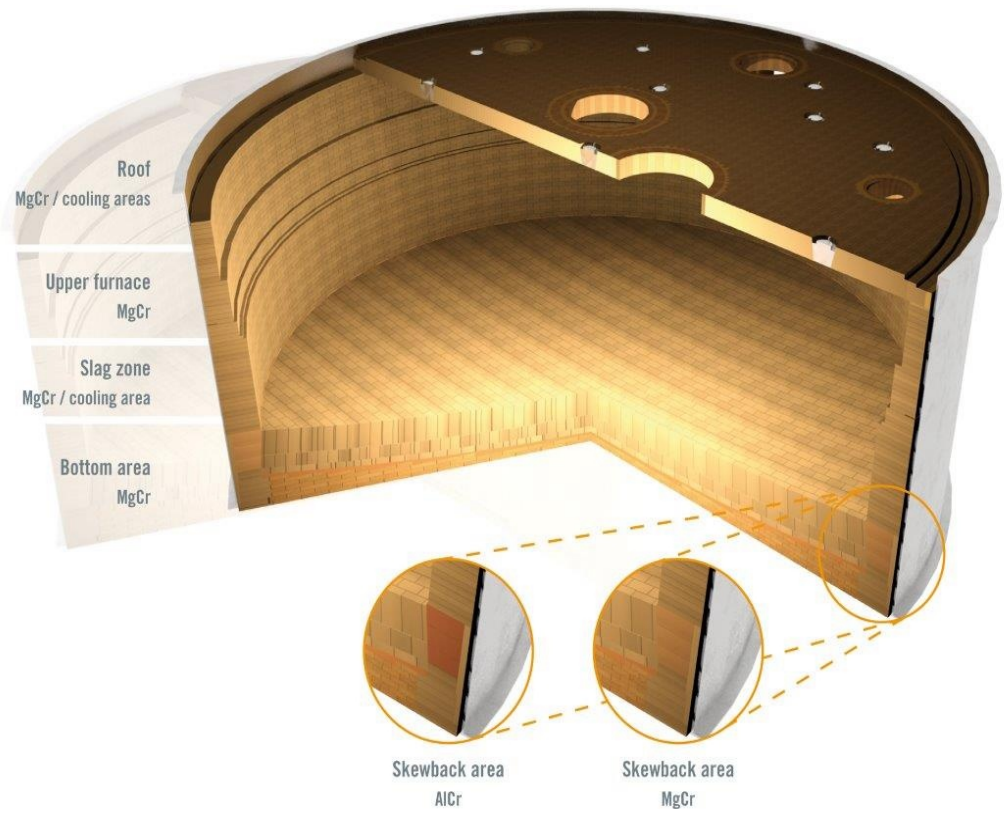


Figure 9: Example of a 3D model of the entire refractory lining of an submerged arc furnace

The complete 3D drawing allows a closer look at any furnace area, and provides step-by-step installation instructions for this area, for the installation team on site.

As an independent refractory supplier without any production site or contract to refractory producers, PolyMet Solutions selects the best available material quality, providing independent and process optimized concepts. Our material list is totally neutral and independent of any manufacturer. This allows an independent order for refractory material according to the provided quality concept. In addition, PolyMet Solutions provides full service in terms of ordering, shipping, and delivery, including supervision on site. Based on the metallurgical and process know-how, the decision about the best available refractory material must be considered individually for every customer and application.

For rectangular furnaces, the overall performance of the lining has been improved by features such as: modifying columns in the corner (see Figure 10), termination of a sub-hearth by letting the lining pass through the working lining, and placing lintels above the inspection doors and the tapping holes.

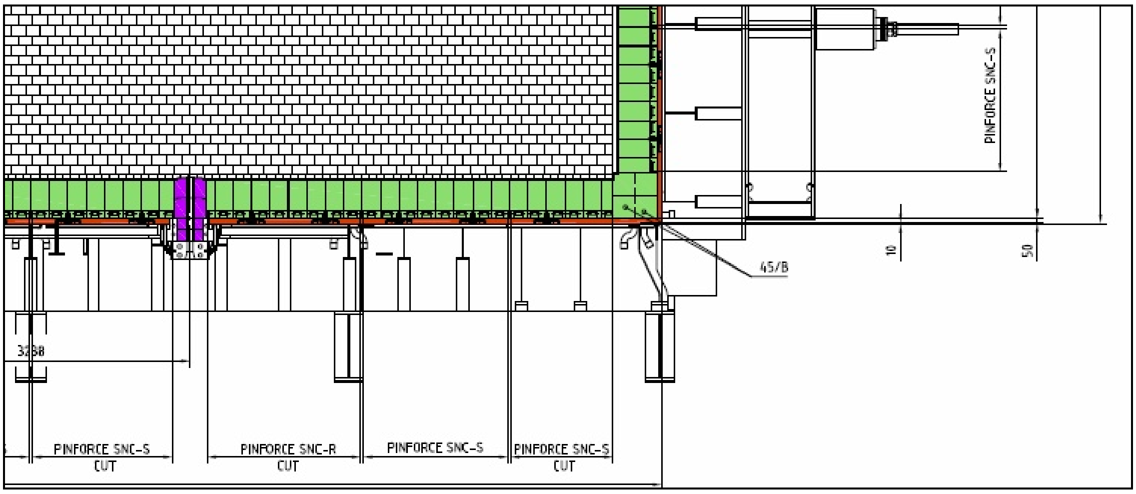


Figure 10: Example of a refractory binding system for a rectangular furnace

Metix has an entire database of refractory quality concepts applied to ferro-alloy furnaces, and applies a similar approach to that outlined above. These quality concepts include both insulating and conductive freeze lining solutions. Metix engineered, supplied, installed, and commissioned the freeze lining of two 81 MVA FeMn/SiMn furnaces in the Sarawak area of Malaysia in 2015 (the so-called "Sakura-Project").

The furnace operators ask for complete service solutions (see Figure 11).

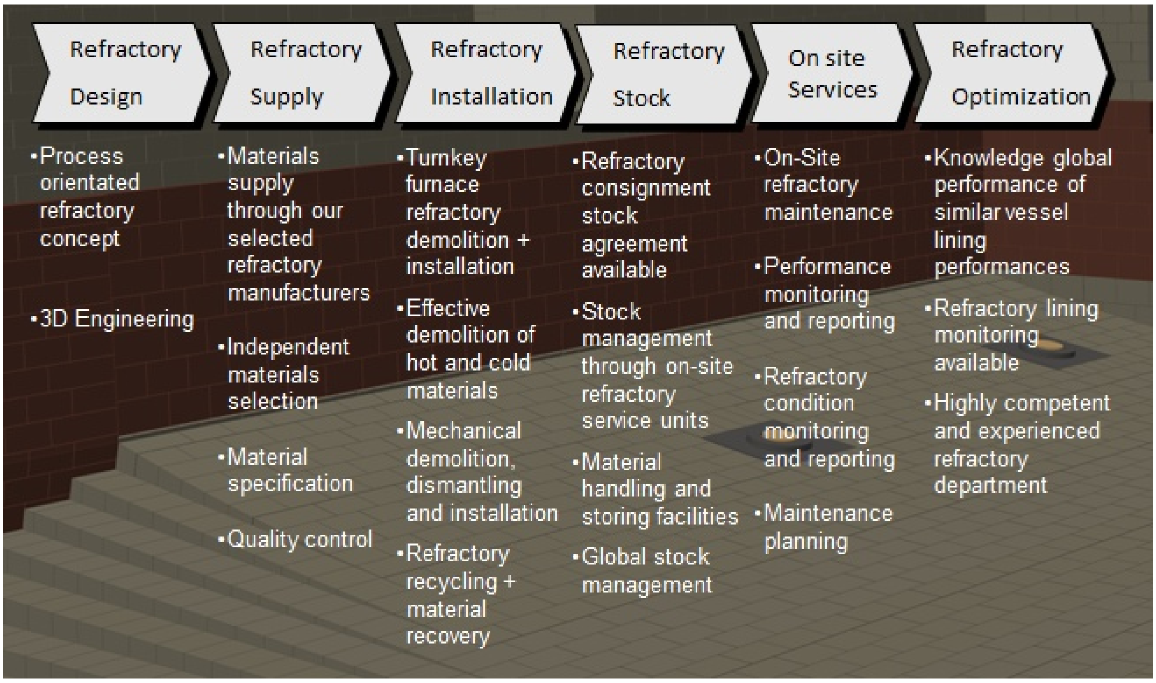


Figure 11: Complete refractory services by SMS group for the ferro-alloy industry

TUNING KITS

SMS also offers several 'tuning kits', which improve the furnace integrity, and lead to a production boost and/or product quality improvement. We are also investigating options to utilize additional purging/lancing/burner/injection systems in electric furnaces for process optimization or to minimize the electrical power consumption.

Furthermore, a robust long-lasting tap-hole and launder design improves the availability of an electric smelter (see Figure 12).

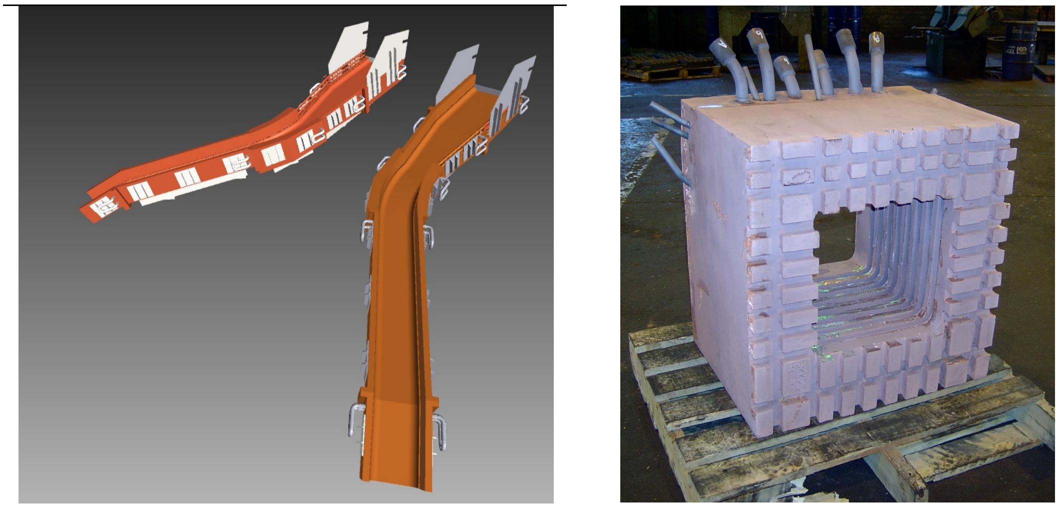


Figure 12: Launder systems and tap-hole for ferro-alloy furnaces

Additionally, we developed acoustic instrumentation systems for accurate monitoring of a 2D temperature image of the furnace, and a radar-based system for measuring the burden profile inside the electric furnace. Furthermore, we also developed systems based on fibre optics for measuring the temperature and the condition of the refractory lining.

Most pyrometallurgical vessels have tap-holes through which liquid metal, matte, and/or slag, are tapped. Due to the frequency of taps by either drilling or lancing, or a combination of both, and plugging, this becomes the weak point in the lining. This essential hole in the furnace refractory has one of the highest wear rates, and is therefore the highest-risk area on any vessel. We therefore pay extra attention to design, safety, operation, and maintenance when it comes to our tap-hole designs. With all these factors taken into consideration, and with the latest water-free ILTEC cooling concepts, we feel totally confident in our designs. The added benefit to a full life cycle of a furnace lining largely depends on a well-designed tap-hole. Crucial criteria include that it should be designed to be maintained safely with as little furnace downtime as possible.

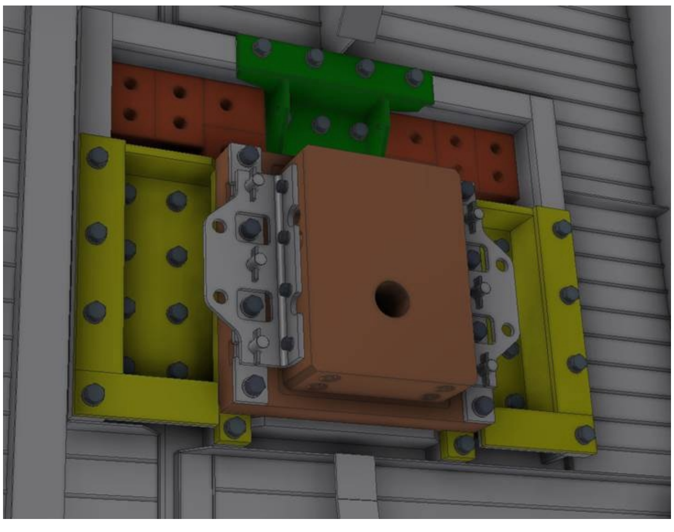


Figure 13: New tap-hole design for ferro-alloy furnaces

SUMMARY

Realising all the described possibilities and tools for improving and optimizing metallurgical processes can only be achieved by looking at the entire process as a whole. Sharing know-how with operators through training courses leads to a better understanding of single furnaces as well as the up- and down-stream factors within the process chain. Via an optimized refractory concept, and in combination with new cooling elements and geometries, the process performance can be maximized. With the support of various modelling tools, the optimized operating mode can be achieved, improving automatization and process control.

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Rolf holds a PhD in Ironmaking from the RWTH Aachen, Germany, where he worked until 1996. He was Project Manager and Head of R+D for NSM in Thailand until 1998; Senior Sales Manager Iron Making and Ferro Alloy Technologies for SMS group in Pittsburgh until 2001; and Head of Submerged Arc Furnace department for SMS group in Düsseldorf until 2015. He is currently Head of the Non Ferrous Metals Department of SMS group in Düsseldorf, Germany, and a Board Member of PolyMet Solutions in Leoben, Austria.
