INNOVATIVE ELECTRIC SMELTER SOLUTIONS OF THE SMS GROUP FOR THE SILICON INDUSTRY

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ABSTRACT

As far back as 1906, the SMS group delivered the first submerged arc furnace. Meanwhile – over more than 100 years SMS has supplied more than 7,500 submerged arc furnace (SAF) plants as well as major components to SMS customers worldwide - operating plants for the production of ferroalloys, silicon, non-ferrous metals and other applications. Metix as well as Paul Wurth which have recently joined the SMS group have significantly increased the SMS product portfolio for our clients and SMS now offers complete process lines for all metal production facilities including a full range of upstream and downstream equipment. This paper will focus on recent SMS developments and projects with respect to electric smelters and submerged arc furnace technology, in particular the production of silicon. The paper will present the recent technology for silicon smelters, which are currently in progress or which have been recently commissioned. Most electric furnaces are considered to be highly energy-intensive units. The high level of electrical energy required is to a large extent defined by the process but can also be influenced by the equipment and the operating practices. SMS has developed a number of measures to reduce the overall energy consumption of these metal production facilities and will meet the requirements on environmental restrictions of the future.

INTRODUCTION TO THE SMS GROUP

The SMS group is, under SMS Holding GmbH, a global player in plant construction and mechanical engineering for the steel, nonferrous metals, ferroalloy and silicon production industries. It consists of the business areas represented by SMS Siemag, SMS Meer, Paul Wurth and the industrial affiliates. SMS Siemag is a part of the SMS group with more than 13,500 employees, which in 2013 attracted sales totaling some EUR 3 billion. Silicon furnaces are designed in the SMS office in Düsseldorf, Germany [1]. In recent decades SMS Siemag has supplied the majority of the SAF's for FeSi & silicon production. With more than 90 references for large scale silicon and FeSi furnaces since 1970, SMS is leading the furnace market (see Fig. 1).

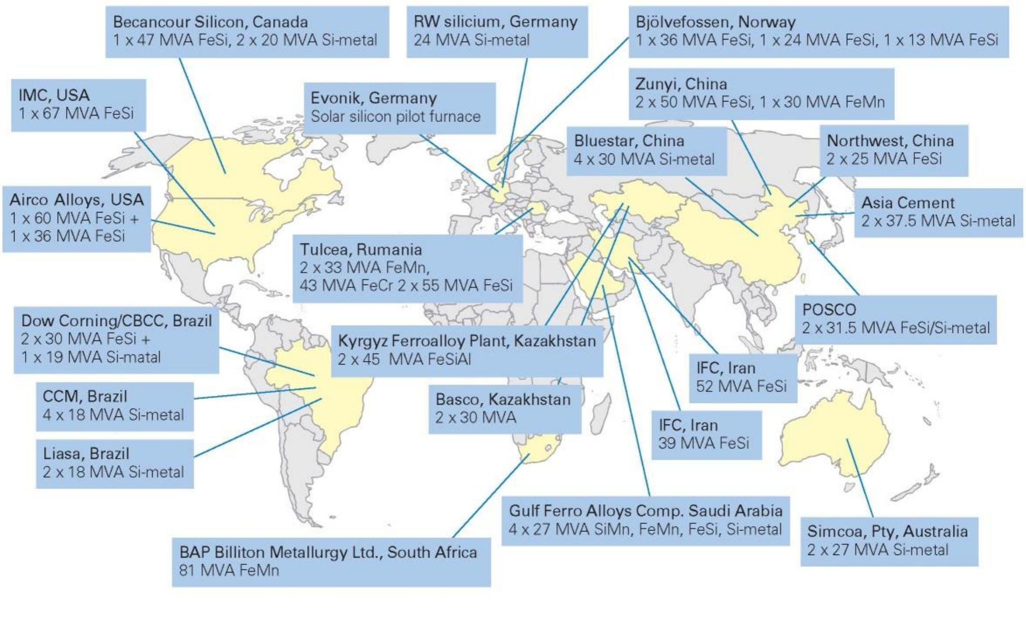

Fig. 1: SMS Siemag milestones in Silicon / FeSi furnaces

Over the past years silicon plants have been commissioned in Korea, China, Kazakhstan and Germany. The most recent reference is a FeSi plant supplied for POSCO in Korea. The following Figure 1 shows a selection of the furnaces installed with the involvement of the SMS group. On 22nd June 2011 the Metix Company which is based in Johannesburg, RSA, joined SMS Siemag AG as part of the SMS Group. Providing active in-plant construction and supplying equipment to the ferroalloy industry for almost ten years, Metix is the market leader with respect to electric smelter technology in the southern African region. Combined with SMS Siemag it takes the group market share of more than 50% of the western world ferroalloys, non-ferrous and precious metals equipment market. Paul Wurth in Luxembourg, with its 1,600 employees and 26 subsidiaries, is worldwide leading company for the supply of complete solutions for blast furnaces, coke ovens and environmental technology for iron works. For submerged arc furnaces and electric smelters, Paul Wurth offers superior equipment such as drilling machines and mud guns (provided by TMT).

HISTORY AND COMPETENCIES OF SMS WITH RESPECT TO SILICON SMELTERS

SMS, a major supplier for the iron and steel industry for the last 100 years, started with the construction of the first submerged arc furnace in 1906 [2]. A 1.5 MVA unit was installed in Horst, Ruhr, Germany, for the production of calcium carbide and was successfully commissioned the same year.

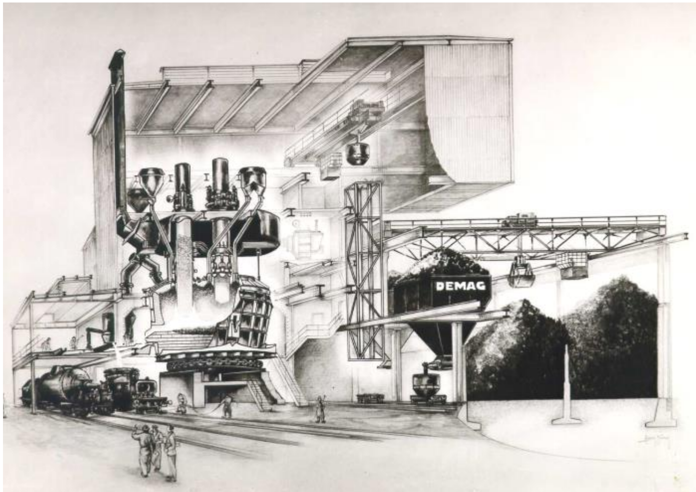

Figure 2: SMS silicon /FeSi furnace as supplied in the 50's [2]

Figure 2 shows a typical silicon furnace of the 1950's as it was promoted at that time. It should be pointed out that the basic principles of the furnace technology have not been changed [2-6]. SMS, however, has progressively improved the design ensuring today a highly reliable and efficient operation. The evolution of the technology, along with the major milestones is shown below:

1906: Reduction furnace (bottom + top electrode)
1935: 15 MVA furnace for silicon production
1951: SAF with rotating gear for silicon production
1956: Compensated low-inductive high current line
1958: Hydraulically regulated electrode column
1966: Encapsulated electrode column
1967: Large-capacity ferro-silicon furnace
1970: Channel type water cooled roof for FeSi/silicon furnaces
1974: Large-capacity silicon furnace
1975: First energy recovery system for 3 FeSi furnaces
1980 Pilot furnace for SG silicon production
2000: New type of control systems
2005: Compact electrode column (suspended type)
2012: Glass fiber tem. measurement of the side wall
2013: Modified arrangement of charging for less stoking
2014: Composite electrode

Additionally, significant developments have improved the safety and environmental conditions in the modern smelter. The furnace control systems also underwent a significant evolution in past decades. The very first furnaces were completely manually controlled. Since the end of the 1950's, SMS SAF's have been equipped with electrode controllers. Today's advanced submerged arc furnaces make use of modern computerized control systems.

SILICON MARKET

After a prolonged period of lower silicon prices, the market appears to be recovering. Independent market research institutes as well as the producers are optimistic for the immediate future [7-8]. For 2015 a stronger demand for silicon is predicted [6]. It is also apparent that, due to high energy demand of the furnaces, new installations are being considered in countries with lower energy cost levels (such as the Canada, US, Middle East& some Asian countries). The production of silicon and FeSi requires the highest specific energy consumption of all submerged furnace applications. The specific energy consumption required for silicon is 10,000 – 12,500 kWh/t. China is still dominant in terms of market share but faces a challenging situation due to increasing power cost, raw material and labour costs along with difficulties in terms of product quality [9]. Additionally, the existing plants, particularly those which are located in high energy cost countries, are being forced to lower their overall production costs (e.g. with energy recovery systems, installation of composite electrodes and increased levels of automation to lower personnel costs). According to the overall situation and several market studies an annual gap of approx. 100,000 t of silicon can be expected until 2018 [10].

TODAY'S REQUIREMENTS ON MODERN SILICON SMELTERS

In order to remain competitive in the market, operators ask for a maximum possible silicon production capacity per unit, high silica fume quality at lowest possible costs (only achievable with minimized electrical losses, implementation of energy recovery systems, maximum plant availability and advanced control systems) [11-12]. Furthermore, the units are expected to operate reliably, even under variable operating conditions. The design needs to cope with fluctuating raw material properties (in terms of physical and chemical characteristics) due to changing mining conditions and the need to find lower cost alternative sources of raw materials and being independent from political influences. Most important is to ensure the maximum possible plant safety and to install adequate gas cleaning systems to achieve the lowest impact to the environment and optimum working conditions for the employees. Finally, the product quality should be reliable and able to meet the specifications of the end users. The following sections will describe SMS's solutions, to meet the requirements for such systems.

TECHNOLOGICAL ASPECTS OF MODERN SILICON SMELTERS SUPPLIED BY SMS

The principle of a submerged arc furnace might look simple. The SAF works with electrical energy which is converted into heat using the electrical resistance of the burden and in the arc between the tip of the electrode and the hearth. The electrodes are submerged in the raw materials and the current passing from the tip of the electrodes to the hearth and between the phases provides the required energy exchange between electrodes in the cavern and the raw materials and intermediate products. The key equipment of a submerged arc silicon furnace is illustrated in Figure 3. A typical furnace is based on a circular rotating shell with 5 tap holes. The furnace shell is refractory-lined including carbon for the hearth and lower side walls of the crucible. The furnace hood is water cooled by channel cooling system, and incorporates glands, openings and seals for the electrode columns, charging pipes and off-gas ducts [12]. Electrical energy is transferred into the furnace via pre-baked carbon or graphite electrodes, in some applications with Søderberg or Aluminum-casing electrode. The composite electrode is also utilized in numerous furnaces worldwide. The electrode column assemblies contain all equipment required to hold, slip and move the electrodes as well as to regulate their penetration into the furnace burden. All operations on the electrodes are performed hydraulically [13]. Electrical energy is normally supplied from the furnace transformers via high current lines, water-cooled flexibles, bus tubes at the electrodes and the contact clamps into the electrodes. Today, control and supervision is carried out by a PLC and visualization system [14]. A back-up for manual operation is also provided in the control room. The process gas is combusted inside the furnace hood through the controlled addition of combustion air and is transferred through the off-gas duct to the boiler (if any) and bag house where it is cleaned.

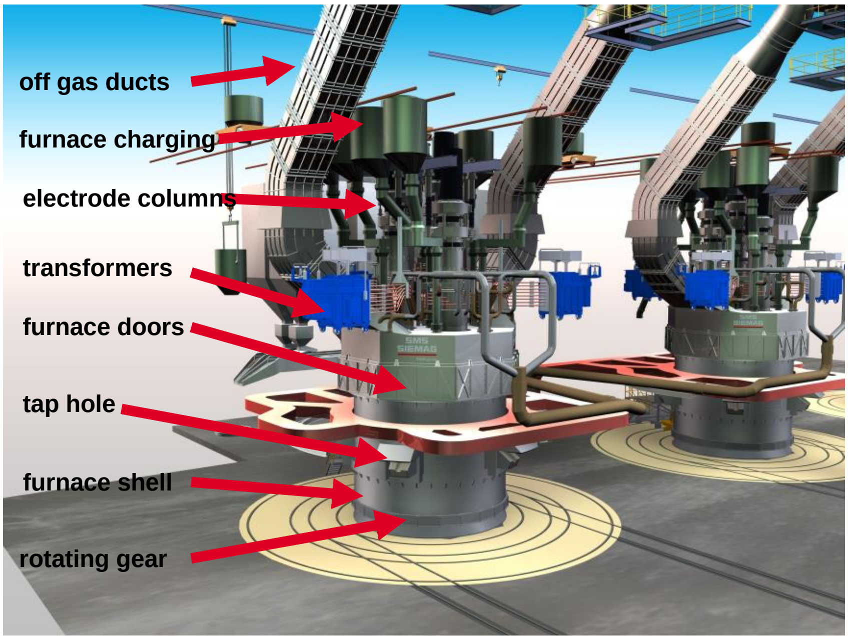

Figure 3: Modern silicon furnace

Day bin and furnace charging systems

For an optimized furnace operation the generation of fines as well as insufficient mixing or excessive segregation of the furnace charge has a negative impact on the silicon process resulting in a lower production at higher specific energy consumption levels, lower NO_x-values as well as lower yields [21]. The SMS design today allows for the mixing of individual, accurate and smaller batches to the furnace bins. The batches are typically transported either via a conveying system or using a specially designed bucket feeding system to the furnace bins. This is a fully automated operation. The bucket feeding system is recommended, when the proportion of charcoal exceeds 50% of the reductant mix. The two-compartment bucket allows for separate handling of the fragile charcoal in the batching operation until the filling of the furnace charge bins in order to avoid excessive fines generation. Such a system is operating successfully at the two furnaces supplied to Simcoa in Australia.

Electrode column

One of the most critical components of a silicon furnace is the electrode column(s). Picture 4 shows the most recent SMS design for pre-beaked carbon electrodes. The fail safe, hydraulically actuated electrode holding and slipping device prevents any uncontrolled slipping, even in case of a complete power outage or malfunctioning of the hydraulic plant. The durable contact-clamps provide highest possible energy transfer to the electrode. Picture 5 show the current and potential distribution affected by the magnetic field in one electrode and surrounding high current copper tubes [15]. Because of the optimized design of the copper tubes in the direct vicinity of the electrodes electrical losses caused by the magnetic induction could be reduced. Modern SMS furnaces are equipped with a suspended electrode column. With this arrangement, the height of the electrode column is reduced (by several meters) which saves costs in the construction of the building and results in less electrode breakages. In case of unforeseen events, the lower part of the electrode column can hold the weight of the electrode using the hydraulically actuated pressure ring. This reduces downtime and lost production following an upper column electrode failure [16-17]. The electrode system demonstrates its reliable performance even in the harsh environment of the silicon furnace and has long life.

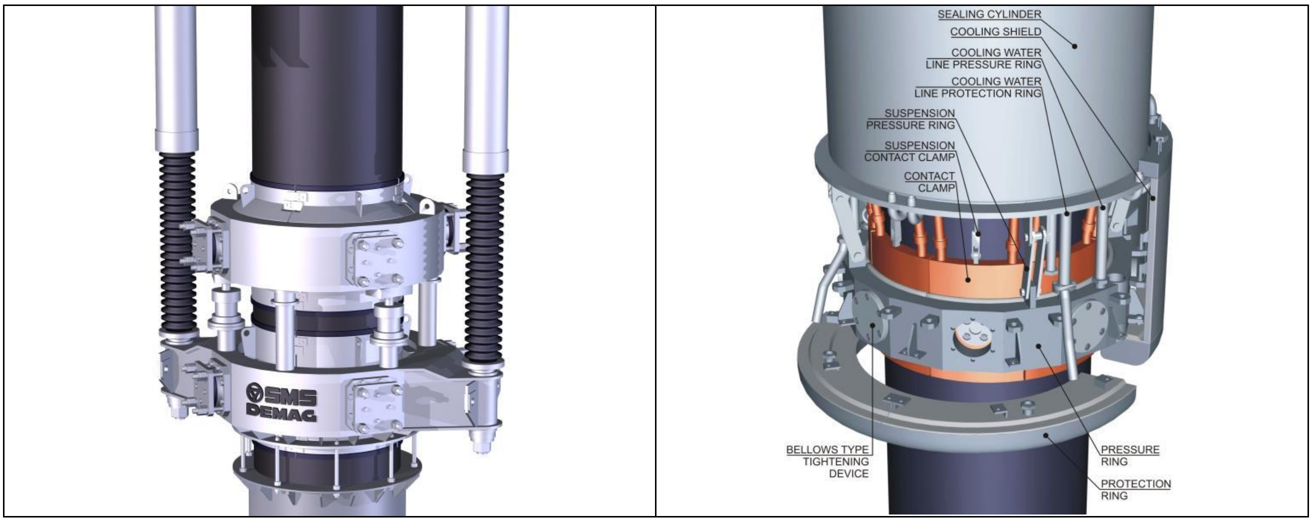

Figure 4: Electrode system for a modern silicon furnace of SMS

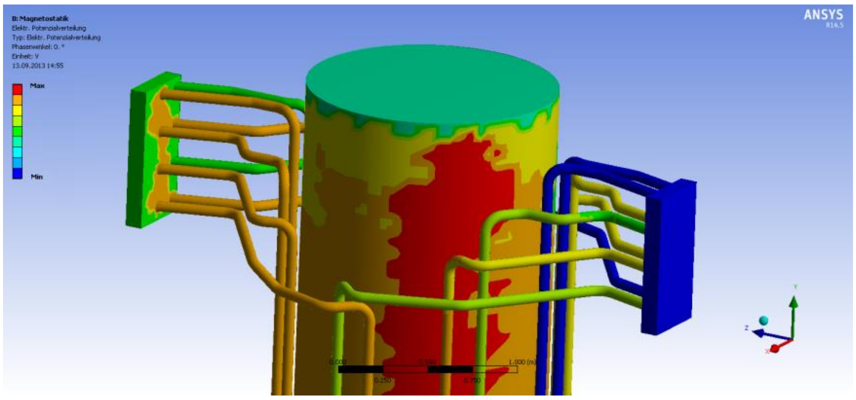

Figure 5: Potential distribution in high current lines

Composite electrode

The composite electrode is highly discussed among silicon producers. Today, around more than 30 of these systems are installed in furnaces worldwide. Mainly such systems were developed over the past two decades by operating companies and are available under license from certain providers. Especially for larger capacity furnaces (> 26 MW), such systems are virtually compulsory due to the larger electrode sizes, which cannot be provided economically readily by pre-baked electrode suppliers. Furthermore FeSi furnace has been converted into silicon furnace by using this technology. The system has its benefits and drawbacks. It allows the construction of mega furnaces and saves up to 50% of electrode costs (due to the substitution of pre-baked electrode material with cheaper electrode paste) [22]. Composite electrodes also eliminate the weak point in the electrode column of the connection between electrode segments. On the other hand, it adds additional complexity in the silicon operation. Therefore, we recommend such systems primarily for experienced silicon producers. SMS has acknowledged the trend to the use of composite electrodes (see Figure 6).

The combination of the composite electrode technology with the SMS compact electrode columns has the advantage, that the pressure ring in the lower section of the electrode column can put a controlled pressure on the lower section of the steel casing, allowing an additional control when pushing the baked electrode through the casing. It is assumed that the electrode consumption as well as the specific energy consumption remains unchanged. This has been confirmed by numerous operators using composite electrode systems.

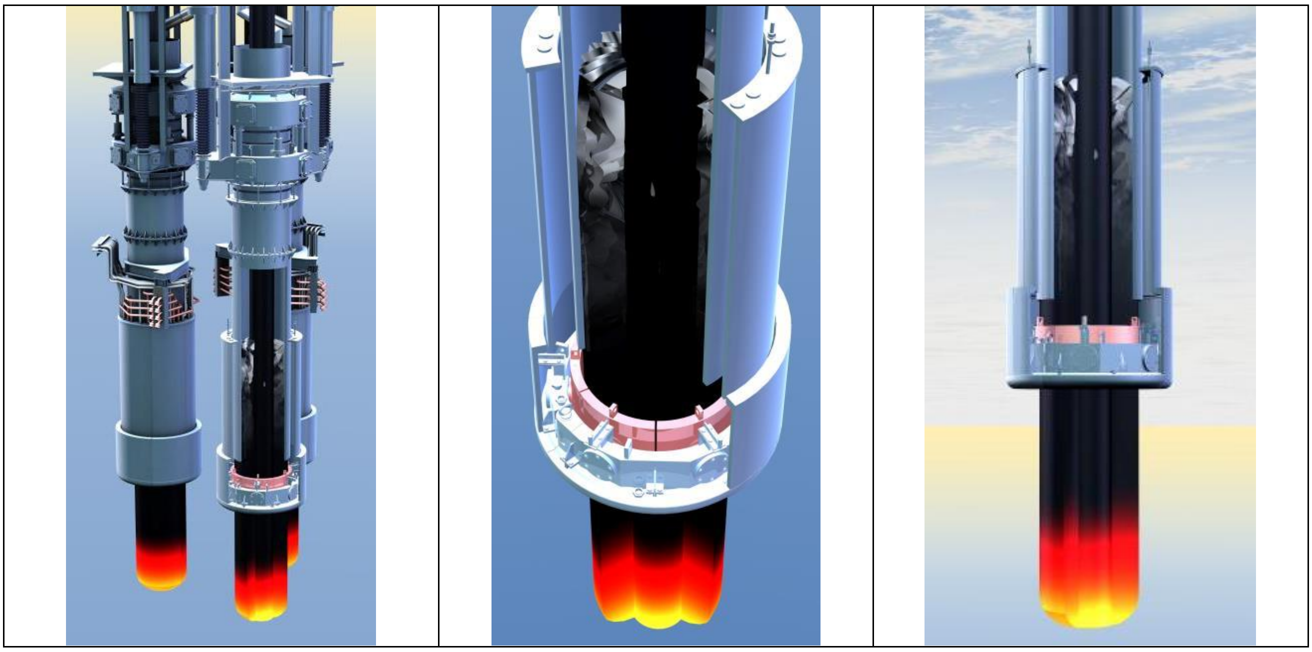

Figure 6: Composite electrode for SMS silicon furnaces

Channel cooled furnace roof

The furnace roof has to cope with extreme conditions in a silicon operation. When blows occur, the gas stream shooting out of the burden can reach temperatures of up to 2,500°C. The roof therefore faces extreme temperature fluctuations. In order to improve the integrity of the roof, SMS has designed it with a channel type cooling system [17]. No welds are exposed on the hot under side of the roof, which minimizes the risk of potential water leaks (see Figure 7).

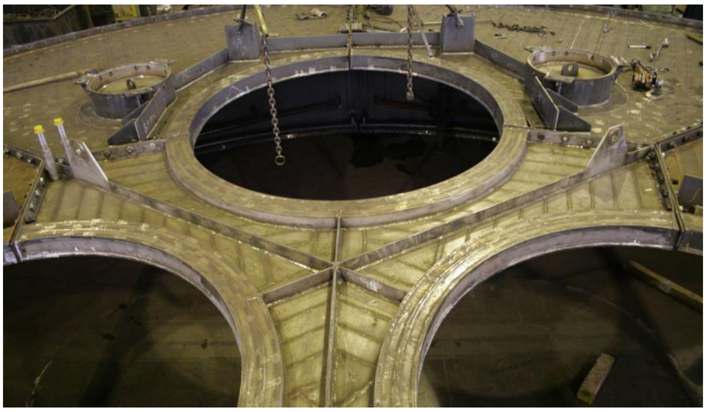

Figure 7: Water cooled roof of an SMS silicon furnace

To further reduce any operating risk resulting from water leaks, today furnaces are additionally equipped with a water leak detection system which even detects any small water leak. The roof also incorporates a pitch circle adjustment system allowing the pitch circle diameter of the electrodes to be changed. This is necessary if the raw materials are changed and improves the flexibility in terms of fluctuations in raw material characteristics. It also assists with optimization of process efficiencies following commissioning.

Door design

Today's furnaces are equipped with doors allowing control of the air going into the furnace for process gas combustion along with cooling air to control off gas temperature (Figure 8). The advantage of an increased off-gas temperature is that the size of the bag house is minimized and the furnace is suitable for connection with an energy recovery system. The newly developed design allows good access from all sides of the furnace for stoking by minimizing uncontrolled air flow into the furnace cover and minimizing contamination of the environment.

Figure 8: Doors of a SMS silicon furnace operating at nominal load

Within the context of the increased off gas temperature, SMS is testing development from TMT (JV between SMS and Dango and Dienenthal) for 2d top gas temperature measurement inside the gas hood to have true gas temperature reading for better control of the ingress air going into the furnace through the open doors. Several transceivers, each operating as transmitter and receiver, are installed on the circumference of the gas hood. Each transceiver emits sounds recorded in turn by the other transceivers. The speed of sound is directly proportional to the actual gas temperature. A high performance processor calculates the actual gas temperature in-between transceivers after each sound emission. Stoking activities can be planned accordingly.

Fume extraction

The fume extraction of the SMS furnace guides the fumes, via a duct system, back under the furnace roof, sealing at the same time the electrode glands and feeding tubes. It is also injected through the outer rim of the roof back into the furnace forming an air curtain to prevent fumes escaping from the furnace into the furnace building. Additionally, it saves one bag house otherwise necessary for conventional tapping fume systems.

Mud gun and drilling machine/Stoking machines

Because of safety aspects, it is advisable that the minimum number of people are working in the stoking and tapping areas of the furnace. TMT has developed a new generation of stoking machines as well as mud gun and drilling machines allowing automated stoking as well as drilling and closing of the furnace.

Improvement of overall electrical efficiency – transformers and high current system

Depending on the furnaces and the application, the electrical energy losses of poorly designed furnaces can contribute almost 20% to the overall energy losses. The design and the material for the high current line, including the electrode column as well as for the furnace roof is highly influencing the specific energy consumption. SMS has optimized the high current line system in such a way that minimizes the reactance of the system and reducing the off-times due to maintenance purposes (Figures 9 and 10).

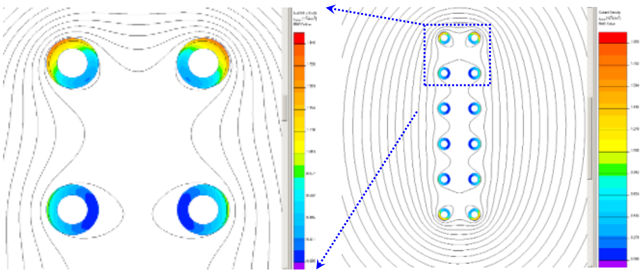

Figure 9: Simulation of high current line clamping frame electromagnetic distribution at transformer outlet

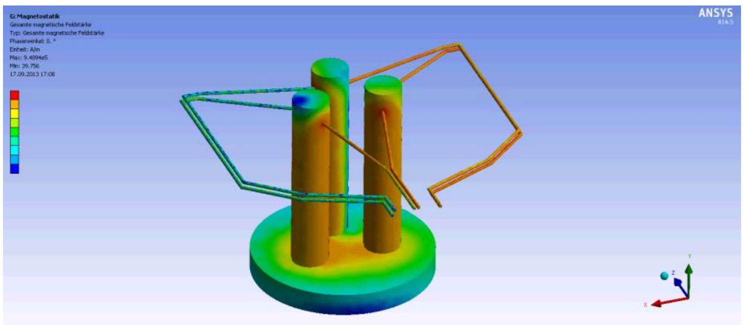

Figure 10: Simulation of high current system including electrodes

At modern furnaces the transformers are placed as close as possible to the electrode. Additionally, using a higher cross section for the high current line system as well as the use of a pressure ring made of copper reduces the overall energy consumption (Figure 11) [16]. The use of copper pressure rings can contribute to a saving of up to 1.5% of the losses in reactive power for high capacity furnaces. For this reason, SMS has developed a patented lower section of the electrode column, which saves energy, has an increased working life than materials used in the past and requires minimal maintenance.

Figure 11: Lower part of the electrode column

Energy Recovery Systems

In semi-open electric smelters, the combustible components of the process gases are fully combusted in the freeboard area above the burden. Today's furnaces are equipped with doors allowing the precise control of the off-gas temperature between 550 to 750°C [18].

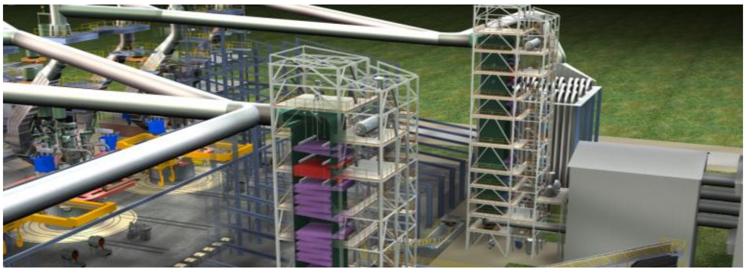

Figure 12: Waste heat boiler for energy recovery from process gas

Instead of cooling the off gas by means of a forced draft cooler or a hair-pin cooler the energy of the off gas is utilized to generate superheated steam within a waste heat boiler. Inside the waste heat boiler convective heating surfaces are located. The boiler is designed with heating surface tube banks for economizer, evaporator and superheater. The upper part of the boiler casing consists of water walls and belongs to the evaporator system. This measure leads to a very high flexibility of the system in case of off-gas temperature peaks etc. The boiler will be operated in natural circulation, thus no circulation pumps are required. The generated superheated steam can be utilized for several applications like e.g. electrical power generation, process steam in a steam net, drives for fans etc. Such an energy recovery unit is being installed at Etikrom, the leading FeCr-producer in Turkey. The boiler produces 2 x 15 tons of steam, which will be converted in a power generation system to 5 MW electrical power. Internal calculation shows that in some Si-metal and FeSi processes up to 30% of the electric power input can be recovered as electrical power (see Figure 12) [19].

OPTIMIZED PLANT AVAILABILTY WITH RELIABLE EQUIPMENT AND PREVENTIVE MAINTENANCE

The stability of the operation is significantly improved with higher silicon recovery levels and reduced heat electrical losses, if the furnaces are operating continuously (minimum interruptions) at or above nominal load, and when the furnace conditions, including the raw materials are kept constant. Furnace interruptions can have a significant negative impact on the specific energy consumption due to the additional energy required for ramp-up of the furnace to nominal load and to stabilize the process. A series of even short shutdowns can have a cumulative effect in terms of disrupting the process and will result in loss of production. SMS is well known for supplying reliable and efficient smelters all over the world. Its design assures highest plant availability levels.

REFINING COMPETENCES

SMS is the leading supplier for refining units applied for the steel industry. It has also extended its competences and transferred its knowhow for Si-metal refining. SMS developed in-house engineering for refining stations together with RHI, which were firstly applied at the furnaces for Kazsilicon and the FeSi plant at POSCO, South Korea (Figure 13).

Figure 13: FeSi refining at POSCO Korea: Refining during tapping (left) and refining station (right)

The unit is refining the metal in the ladle and the air/oxygen mixture is injected via one plug and the refining station is equipped with a separate de-dusting system. To optimize recovery and quality, a skull removing machine and a de-slagging station can be installed specifically for the production of FeSi. The blow pattern of the unit is controlled by the automation system. The refining station reduces undesired elements such as Al and Ca down to the requested off-takers specification. For high purity products the Al content should be below 0,10%, Ca content - below 0,06%, and the Ti contend - below 0,01 %. In order to achieve these values, SMS will critically look at the foreseen raw materials and give advice according to the desired specifications. SMS is also developing the reduction of the impurities of Ti and B through the introduction of special additives, because elements of Ti, Mn and P cannot be removed from the metal during the normal air/oxygen bottom blowing refining [21].

R&D TOPICS

One major reason for SMS's position in the world market is the constant improvement of processes and equipment through innovation. Major milestones are only possible with strong clients. For many years on, SMS cooperates with numerous research institutes and universities as well as a wide range of consultants.

Strategic developments

- Large scale silicon furnaces (>40 MW)
- New process lines with pilot smelter at University of Aachen/Germany
- Mini Submerged Arc Furnaces for ferroalloy and silicon production

Fundamental developments

- Fundamental R+D for new process lines AC vs. DC
- Modelling of various processes

Operational development

- Composite electrode system
- Refining optimization
- Emissions reduction
- Clean environment analysis

Slag cleaning

SMS has developed a process for the cleaning of copper slags by using DC technology that increases separation effects between conductive and nonconductive materials in their liquid state. It could be considered to process slag from special silicon production, like solar grade processes and investigate whether this improves recovery of upgraded silicon products. A second effect to investigate is the removal of B and P in such a unit by a variation of slag refining.

Mini SAF

The Mini Submerged Arc Furnace (Mini SAF) is a simplified version of a small capacity smelter (< 12 MVA). The goal is to develop the lowest possible cost unit. Charging is carried out manually, the electrode column is simplified and the unit does not require a hydraulic system. Additionally, the concept saves significant costs for the civil and building construction portion of the project. It must be emphasized that the Mini SAF meets international safety and environmental standards. Apart from silicon, it will also be possible to produce FeSi, FeMn, SiMn and FeCr in these units. SMS is targeting smaller companies in developing countries such as India as well as in Asia and Africa [22].

Mega silicon furnace

Going to the other extreme, SMS is also looking for possible furnace capacities for silicon beyond 40 MW. Such a capacity is only possible through the installation of either very large composite electrode systems or by installing 6 electrodes per furnace. SMS supplied a 6-electrode rectangular furnace in the 80's in the US, which is still in operation. This new development investigates the possibility to use 6 electrodes in a circular furnace, including a rotating shell. The improved multiple electrode concept for circular silicon furnaces allows power input of > 40 MW and provides an even power distribution and reduced electrical losses from the furnace resulting in a low specific energy consumption [22].

CONCLUSION

The first SAF has been commissioned more than 100 years ago in Germany. Since then, a remarkable development of this smelting tool has been recognized all over the world, and submerged arc furnaces are now operating in at least 20 different main industrial fields. SMS group can offer a wide and complex product portfolio for AC- and DC-based smelter technology. In particular, the silicon smelters are constantly being improved and today they are the most reliable and efficient units worldwide. Combining a silicon furnace with an energy recovery system is especially recommended for counties with higher energy price level. SMS is prepared to fulfill the requirements for the silicon market regarding increased production units for the near future.

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