Status Report on Pyrometallurgical Ferronickel Production

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Introduction

Stainless steel production is predicted to increase at an annual rate of 5 % /1/. Accordingly, demand for nickel, especially for ferronickel, as a bulk alloy for stainless steel mill melt shops is expected to increase proportionally. In preparation for this market expansion, this paper reviews the current status of, and future opportunities for nickel production.

Overview of current Nickel production technology

At present the majority of nickel is produced with pyrometallurgical smelting based on Submerged-Arc Furnace (SAF) technology.

Two products can be produced with pyrometallurgical smelters depending on the ore characteristics

- Ferronickel from oxidic ores (such as laterites, limonites, garnierites or serpentine containing ores)
- Nickel Matte from sulfidic ores

In addition, extensive development is presently being carried out on the hydrometallurgical process route. The major focus of these programs is to lower the cost of nickel production.

Murin Murin from Anaconda Nickel, supported by Glencor and Anglo America is trying to produce nickel with a pressurized acid leaching process (HPAL) at industrial scale. It has been reported that the availability of the plant is low, and the expected cost advantages at the industrial level have not yet been reached. The original production cost was estimated to be less than 2 US $/lb. Currently, the plant produces nickel for 4 to 5 US $/lb. The companies' forecast is still positive, even if the original goals for investment and operating cost have not been achieved. /2/

Today it is apparent that nearly all future nickel production project expansions are based on pyrometallurgical ferronickel smelting in submerged-arc furnaces. /3/

Leading ferronickel producers such as ERAMET, Cerro Matoso, LARCO and ANTAM are planning to increase their ferronickel production significantly by increasing the existing smelting capacities or by installing new production units. Newcomers such as Loma de Nickel are also planning to enter this active market.

Lowering production costs for FeNi production using SAF technology

Many submerged-arc furnace users are looking to reduce operating costs by installing state-of-the-art, high power smelting units or by redesign of existing units.

Production costs can be attributed to a few major areas including: raw materials, energy, electrode paste and refractory.

Minimizing these costs can be achieved by taking the following measures:

A) Proper mining management

It is important to maintain accurate control of Ni-grade and material characteristics (such as SiO_2/MgO ratio, Fe_xO_y content, L.O.I. and fines content). In addition, a homogeneous mix must be prepared in a proper sized stock pile to deliver suitable raw material for the subsequent processing lines.

B) Controlled kiln operation

The SAF feed preparation requires an accurate control of carbon, calcination and a high and stable degree of pre-reduction (stable calcine deviation range should be less than 0.5 %, the Ni-metallization degree should be in the range of 15-25 % and a Fe-pre-reduction of 80-85 % should be achieved).

Preconditions for a successful kiln operation are:

- constant supply of feed to the kiln regarding quantity, sizing of the ore and carbon materials and ore/carbon ratio;
- high strength of pellets in order to avoid dust formation;
- optimized degree of filling degree and rotating speed;
- stochiometric operation to avoid problems like ring formation, bad calcine and low reduction efficiency;
- accurate control of the temperatures inside the kiln high enough to provide the optimum conditions for calcination and prereduction but below the level where rings are formed;
- close control of the length of the flame whereas gas as fuel is giving the best results.

C) Dust recycling

Higher yield can be achieved with the recycling of dust from dryer and kiln. The dust should be agglomerated on pelletizing units before it is charged back, with the regular feed, to the kiln.

Several other process routes have been investigated, like briquetting, sintering or smelting the dust in plasma or induction furnaces. Technical problems depths and the respective tap-hole arrangements)

- charging point locations
- shell cooling system
- refractory concepts

Slag operation practice: System FeO - MgO - SiO_2

The metal's Ni-content is a function of the Ni/Fe-ratio in the calcine and the FeO-content of the slag. It is possible to adjust the FeO content in the slag within a certain range by adding the required amount of carbon to the ore or to the calcine. The carbon content is related to the FeO content in the slag as shown in Figure 1.

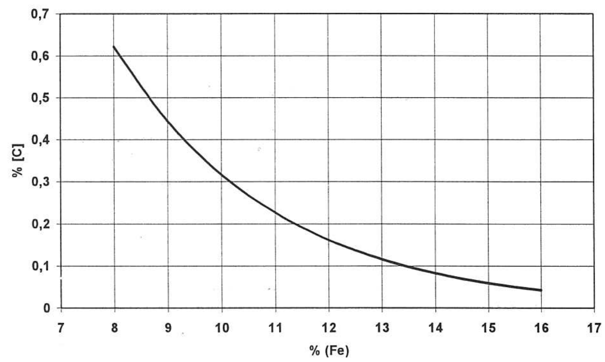

Figure 1: Carbon content as a function of slag FeO content

It influences the metal temperature (see Figure 2).

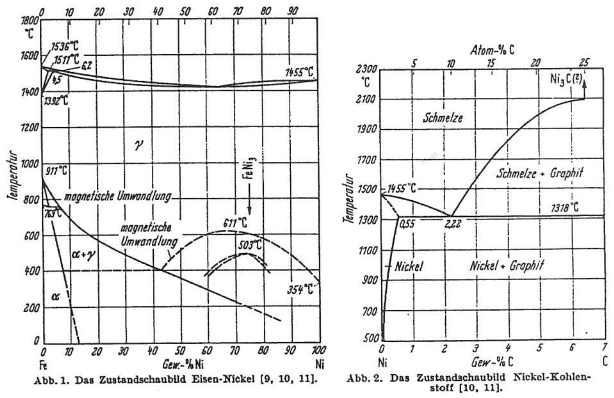

Figure 2: Ni-metal temperature as a function of carbon content

Decreasing FeO content of the slag raises the slag viscosity as shown in Figure 3. /5/

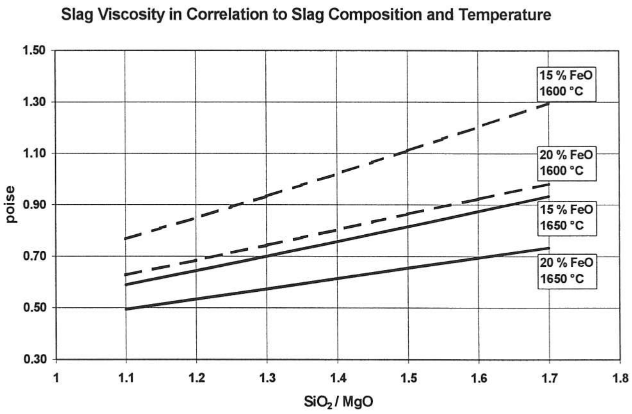

Figure 3: Slag viscosity as a function of slag FeO content, temperature and SiO_2/MgO ratio

Higher percentages of FeO in the slag also lowers the slag electrical conductivity (shown in Figure 4), and the FeNi quality drops as more iron is reduced and the Fe content increases.

notwithstanding, it was the economics that made these processes unattractive. /4/

Another interesting alternative is the direct charging of dust into the submerged-arc furnace through hollow electrodes. This is technically feasible by proper dimensioning of the electrode pressure system and proper sealing to maintain the pressure in the smelter. However, the amount of material charged in this manner is limited by the feeding capacity of the hollow electrode system. Furthermore, dust that is not completely calcined may cause occasional slag foaming when fed directly into the slag bath.

D) Slag utilization and slag energy recovery

Even though FeNi production results in 8 to 12 times more slag produced than metal, attempts to recover energy from the slag or to utilize the slag as a raw material is not very common.

Currently, only Japanese companies make attempts in this area. Some FeNi producers sell the slag to the fertilizer industry or as a feed for rockwool production. In some plants the energy of the liquid slag is used to produce pre-heated air for ore drying where up to 30% of the energy has reportedly been recovered.

In the near future utilization of the slag and its energy must be considered more seriously to lower overall production costs.

E) Submerged-Arc Furnace operation improvement

Optimizing the operation of the SAF is one of the primary ways to reduce operating costs. Major parameters for submerged-arc furnace operation are:

- **Selection of right furnace design**
- **Slag operation practice**
- **Operation mode**
- **Energy transfer mode**
- **Metal and slag temperature control**
- **Cooling mode**

Since each item significantly influences the process economics, they are described below more in detail.

Selection of correct furnace design

The design of the furnace encompasses:

Electrode system: electrode diameter and electrode PCD

Furnace transformer: providing the necessary current and voltage range

Furnace proper:

- furnace shape (rectangular or round)
- hearth diameter
- hearth dimensions/shape (taking into account the required metal and slag

Choke feeding provides certain benefits in terms of achieving good operational parameters with minimized production costs. Charging tubes are arranged on the periphery close to the furnace side-walls as well as the furnace center.

Two plants in Japan operate smelters in which the majority of the charge is introduced to the center. For this practice the permeability of the mix is highly important.

This mode of operation ensures good side-wall protection, minimizes roof attack by radiated heat and keeps the energy consumption low, because the electrodes tips are covered by calcine.
For successful choke feeding it is important to minimize the amount of fines in the calcine and to assure a high degree of calcination.

Independent of the energy transfer mode (arc or resistance) this charging procedure provides stable and safe furnace operation with regard to slag and metal temperatures and wall temperatures.

A certain amount of calcine charged through the outer tubes will be melted when the furnace operates at a constant load. If the slag temperature exceeds a certain limit, the energy introduced to the furnace has to be compensated by feeding a surplus of calcine to the furnace. This is achieved with a time-sequence-controlled automatic charging program. Between 10 and 30 % of the total charge contributes to the slag temperature control management.

Calcine sizing also affects its flowability. As the amount of fines increases a crust may form preventing material from reaching the electrodes. Consequently, the slag bath in the center of the furnace becomes unnecessarily overheated.

Charging poorly calcined material to the center of the furnace can cause a similar result. The residual L.O.I. is emitted as soon as the material enters the slag bath, which can result in slag foaming and/or crust formations around the electrodes. This could interrupt the supply of calcine to this area.

Some low grade calcined ores (material with too many fines, poor calcination, liquidus temperature either very low or high) require batch feeding.

If the slag liquidus temperature is too low, slag superheating may be necessary to achieve the appropriate nickel metal temperature. This temperature increase is not feasible when larger quantities of calcine melt leaving insufficient energy in the system for superheating the slag. The result is that the metal remains cold.

For high slag liquidus temperatures it may also be difficult to raise the slag temperature because energy input to the furnace melts the calcine being continuously fed by choke feeding. If the rate of feed is too high, energy will melt the calcine instead of raising the slag temperature. This can result in a highly viscous slag, which is difficult to tap.

The aim of batch feeding is to cover the surface of the slag as completely as possible with calcine to minimize heat radiation against the upper side-wall and roof lining. Therefore, accurate furnace feed control will improve the operation.

At Cerro Matoso this requires one operator who closely monitors the furnace condition and distributes the feed to the furnace accordingly. Excess feeding in a particular area tends to result in formation of crusts and slag foaming. For batch feeding the furnace should be operated with an open bath in the vicinity of the electrodes.

Figure 6 shows typical furnace operation with batch feeding necessitated by a very low slag melting temperature (approx. 1320°C). In this particular case it is obvious, that mining management, and in particular, proper blending, is very important.

Figure 6: Furnace operation with batch feeding

Energy transfer mode

Resistance heating is a common practice used for pyrometallurgical FeNi-production. Due to the large amount of slag created in the production of FeNi, resistance heating is suitable for this kind of the operation.

Arcing operation was introduced for various reasons. Primarily, it was found that the power input by resistance heating was limited. In addition, refractory erosion was caused by the acidity of the slag and the high electrode currents. These caused breakouts at the slag/metal interface.

Therefore, it became obvious, that higher power inputs in existing furnaces could only be achieved by substituting the arc heating partly for resistance heating (i.e. raising the electrodes above the slag bath, while maintaining calcine coverage over the electrode tip). If the electrodes cannot be shielded by calcine due to excessive fines or limited calcination, it is common operator practice to pile the calcine against the electrodes. Figure 7 shows the operation with a shielded and non-shielded arc

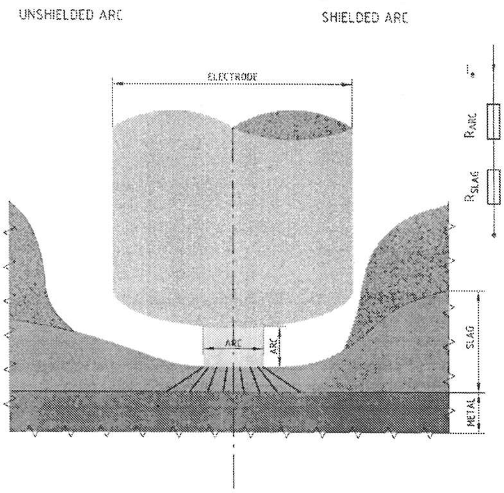

Figure 7: Operation diagram with shielded/non-shielded arc

Melting tests have been carried out with slags with different SiO_2/MgO-ratios and FeO-contents shown in table 2.

	S15-1,1	S15-1,3	S15-1,5	S20-1,1	S20-1,3	S20-1,5
SiO_2/ MgO	1.1	1.3	1.5	1.1	1.3	1.5
% FeO	15	15	15	20	20	20

Table 2: Slag compositions

Figure 8 shows an overall view of slag melting behavior with different SiO_2/MgO-ratios and FeO-contents /6/.

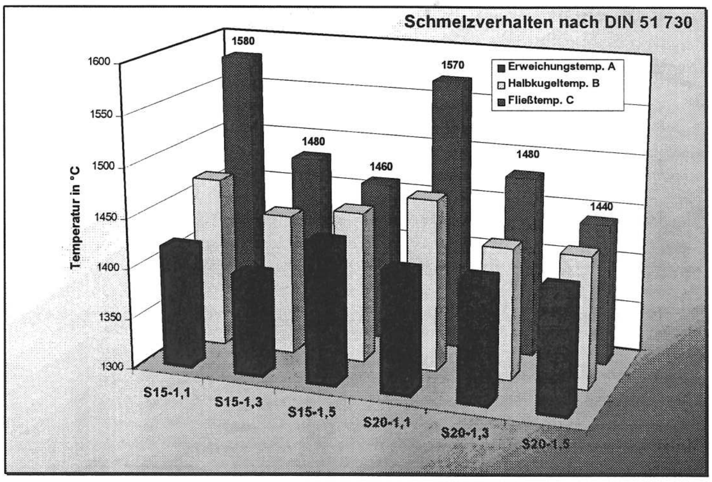

Figure 8: Slag melting behavior with different SiO_2/MgO-ratios and FeO-contents

With a decreasing SiO_2/MgO-ratio the softening range increases from 10 °C to 50 °C and the melting range is between 100 and 110 °C with a ratio of 1.1:1.

Accordingly, resistance heating is not appropriate for this specific material because it would cool down the slag surface when charged onto a slag bath and hence become soft and viscous. This feed would not melt. Therefore, this material should be fed near the electrode tip where the hot arc will melt it immediately.

Electrode regulation is also an important aspect of furnace operation. Because the voltage gradient across the arc is up to 10 times higher than in the slag the electrode regulating system must be capable of a rapid response in order to maintain a stable arc. However, the large mass of the electrode limits rapid electrode movements.

With regard to regulation the configuration of the furnace affects the regulation technique employed. Circular furnaces operating in arc mode can regulate referencing current or impedance. In addition, the voltage in large capacity is usually stabilized by thyristors. Rectangular furnaces with six electrodes in line cannot be regulated to a current set point because each pair of electrodes is supplied with power from a single phase transformer. In this case only impedance control is possible. But again, voltage stabilisation is performed by thyristors.

A typical transformer diagram of a high power 100 MVA FeNi furnace is shown in Figure 9.

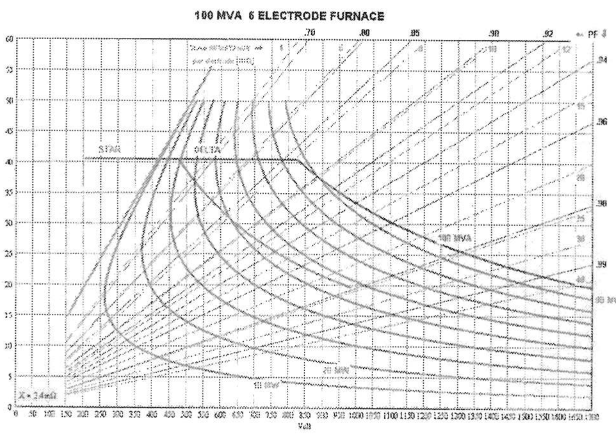

Figure 9: Transformer diagram of a 100 MVA FeNi furnace

The diagram covers a wide range of possible operating resistance per electrode.

The graph does not clearly indicate the transition from resistance heating to arcing or the partial substitution thereof.

For arc mode operation insulation of smelting system is of significant importance due to the higher operating voltages.

Present experiences of several arc-mode-operating-smelters show a replacement of resistance heating by arc heating of up to 40 percent. For future plants arc heating may account for up to 70 % due to further calcine preparation improvements (such as calcination, agglomeration and chemistry).

The advantages of arc operation can be summarized as follows:

- Increased Power Input - The power input in an existing furnace based on resistance heating can be increased significantly with partial arc operation (in some cases even doubled).

- Lower Energy Consumption - The overall energy consumption can be reduced because of less electrical and thermal losses, even if occasional radiation losses result.

- Less Refractory Wear – This is due to improved energy distribution on the smelter side wall and lower slag levels.

Given the above, the trend is very clear in that an increasing number of nickel smelter operations are partially substituting resistance heating with arc heating.

Metal and slag temperature control

The metal liquidus temperature is influenced by the carbon content, and the carbon content correlates with the reductant reactivity and the active slag FeO content as is can be seen in Figure 10.

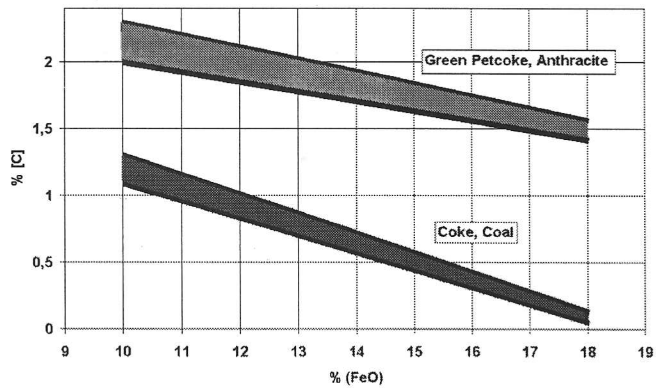

Figure 10: Carbon content correlated to reductant reactivity and slag FeO content

The metal tapping temperature should be approx. 80 to 100 °C above liquidus temperature to avoid sculling in the ladle (i.e. a loss of yield) and to account for further temperature drops for subsequent metal refining/treatment steps such as secondary metallurgical treatment in ladle furnaces or refining in converters.

The liquidus temperature of the slag strongly correlates with its SiO_2/MgO-ratio and the FeO content. Assuming a target metal temperature of 1450 to 1480 °C the operating slag temperature will be in the range of 1580 to 1650 °C. In this case the slag has to be superheated by at least 50 to almost 300 °C.

Depending on the mode of charging and energy transfer, there are different procedures to obtain the necessary metal and slag temperatures.

When a furnace is operated in resistance mode, the depth of electrode immersion in the slag controls the temperature profile. In resistance mode the energy input is divided into horizontal and vertical components. With shallow immersion of the electrodes heating of the slag occurs (larger horizontal component); with deeper immersions the temperature of the metal can be increased (larger vertical component). Energy input and charging rate must accordingly be matched to control the temperature level.

When utilizing arcing mode melting of the calcine it is important to remember that heat is primarily generated at the electrode tips.

Accordingly, the metal is indirectly heated by the sensible heat of the slag. The extent of this heating is dependant upon the slag's thermal conductivity. Two measures can be used to increase the metal temperature. The sensible heat of the slag can be raised with further superheating, or the thermal conductivity can be raised by decreasing the thickness of the slag layer. However this second technique is limited since it is advised to maintain a minimum slag layer of 800 mm in modern, large FeNi smelters.

Cooling mode

For a low cost nickel production smelter, an availability of at least 98 % at the maximum power level must be achieved. This availability is primarily affect by the life of the refractory side wall. Since FeNi furnaces operate with a high slag bath level, the heat flux to the side-walls must be controlled using proper cooling so that the slag solidifies on the lining surface (freeze lining). In this way the frozen slag layer protects the refractory.

Refractory wear of the side wall is dependant upon the following factors:

1. ***The magnitude of side wall heat flux which is a function of:***
   - furnace capacity and energy conversion in the slag (resistance or arc heating);
   - super-heating of the slag;
   - furnace geometry;
   - height of the slag level;
   - thermal conductivity of the slag and the refractory lining.
2. ***The chemistry of the slag (such as SiO_2/MgO ratio and the FeO content).***
3. ***The method of charging such as:***
   - choke feeding;
   - batch feeding with a high turbulence/mix level in the furnace;
   - batch feeding with a low turbulence/mix level or even an open slag bath.

In principle, two types of cooling systems can provide enough heat extraction to generate a freeze lining on the side-wall refractory surface. These can be used separately or in combination. These are:

- cooling of the furnace shell with water (water film, spray cooling or intense spray cooling), and/or

- cooling of the slag area with water-cooled copper-elements (placed behind or in between the side wall lining).

Both cooling system principles are designed in a way that cooling water is only used <u>outside</u> the furnace shell for safety reasons.

The cooling of the furnace shell with water film or spray cooling is commonly practiced in most FeNi furnaces. This refractory system consists of bricks with a high thermal conductivity (usually MgO bricks) and a graphite-based paste between the shell and the bricks. The paste also exhibits a high thermal conductivity but it must also exhibit high temperature plasticity.

In addition, frequent grouting ensures sufficient heat transfer and cooling effect for the formation of a freeze lining. For this concept to be successful it is important to select the appropriate lining design and brick quality so that the freezing line forms at a residual brick thickness which is still mechanically stable (i.e. > 200 mm) as shown in Figure 11.

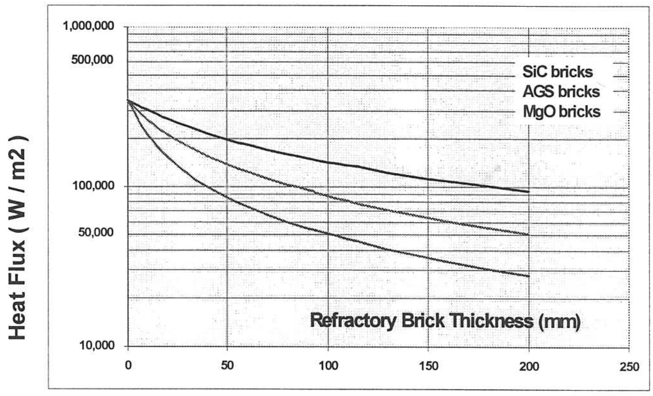

Figure 11: Heat flux in correlation to remaining brick thickness

Figure 12 shows the temperature profile in the side-wall lining, based on an assumed 20 kW/m² heat flux to the lining with constant water spray cooling of the shell.

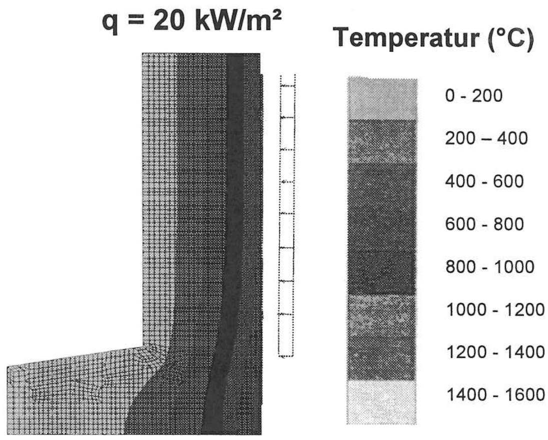

Figure 12: Temperature profile MgO bricks with water film of spray cooling

Since 20 kW/m² is already a conservatively high design figure, the thermal pre-conditions for freeze lining formation are ensured, even when no additional side wall protection is given by the calcine.

However, spray water cooling of the shell can reach its limit, when:

- an existing furnace gets overpowered beyond its original design,
- an ultra high power furnace is designed, or
- the composition of the ore body requires extreme superheating of the slag with minimal protection of the side-wall by calcine.

In these cases more intensive cooling of the slag zone is required, and the installation of copper cooling elements is preferred.

Figure 13 shows the principle of copper cooling elements as provided by SMS Demag.

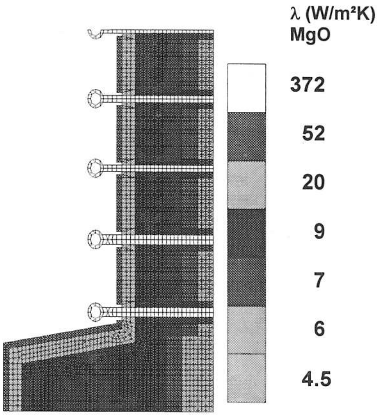

Figure 13: Copper cooling system by SMS Demag

The system has the following characteristics:

- The water passages remain outside the shell.
- The thickness of plates allow the thermal expansion of the lining.
- The bricks are ensured to remain in full contact with the copper elements.
- The system is maintenance friendly (i.e. the copper element is easy to replace.)

Figure 14 shows a temperature profile with a heat flux of 20 kW/m². This figure demonstrates the stronger cooling effect provided by the copper element as compared to regular shell cooling (Fig. 12). For a heat flux below 20 kW/m², copper cooling elements are effective, but are not necessary.

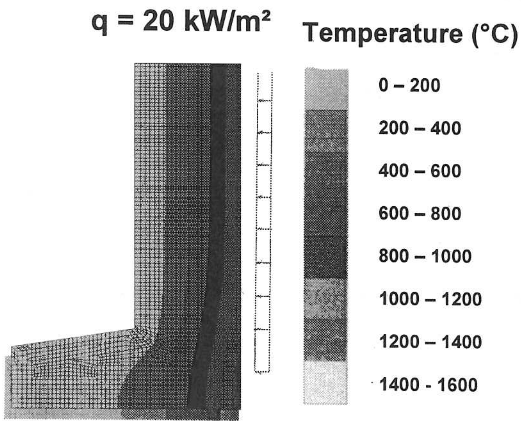

Figure 14: Temperature profile MgO bricks with SMS Demag cooling system

Figure 15 shows a lining temperature profile with a heat flux in the upper slag zone of 40 kW/m² and 60 kW/m² in the lower slag zone. **q = 40-60 kW/m²**

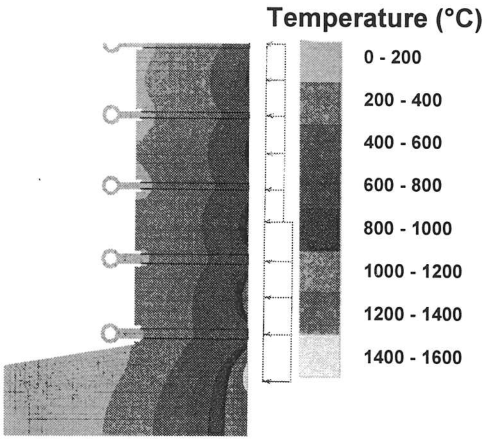

Figure 15: Temperature profile MgO bricks with SMS Demag cooling system

Even under this extreme condition, a freeze lining is ensured. Although this normally does not happen in the FeNi smelting operation, it could theoretically occur in an ultra-high-power arc operation (70 - 90 MW) when a sinter bridge collapses. In this case the arc operating mode would suddenly and inadvertently change to a resistance operation at a high kA level. For each kind of operation suitable cooling systems are available. The new cooling systems ensure high smelting unit availability, and lining life of more than twenty years have been predicted.

Copper cooling elements very effective in prolonging refractory life. Unfortunately, they also increase electrical consumption. Therefore, a thorough study is required on a case-by case basis to determine whether copper elements are both necessary and indispensable.

Conclusion

The demand for nickel is expected to increase over the next few years due to the growth in the stainless steel industry. Accordingly submerged-arc furnace operation is under review, not only for new facilities, but also to increase production and lower production costs for existing facilities. Due to the interrelation of many factors, this requires a holistic view of the whole smelting process. This starts with a good overall plant concept from raw material preparation through smelter operating practices. For existing plants improvements in smelter operation can significantly lower production costs. The primary areas where operations can be improved include slag management, energy input concepts, metal and slag temperature, and effective and balanced cooling systems.

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