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Insulating or Conductive Lining Designs for Electric Furnace Smelting?

J.D. Steenkamp, G.M. Denton and D.A. Hayman

Abstract Design of furnace containment systems can be based on one of two design philosophies: Insulating or conductive lining designs. In insulating lining designs, management of the compatibility between refractory materials and process materials (typically liquid metal and/or slag) is an important criterion for furnace design, and an important process parameter to control during furnace operation. In conductive lining designs, management of the integrity of the layer of frozen material (freeze lining) on the interface between the liquid process material, and the refractory lining, is important. For example in ferrochromium production, both lining design philosophies are applied. The work presented here discusses the significance of lining design philosophy in the context of ferrochromium production.

Keywords Furnace containment · Lining design · Ferrochromium · FeCr

Introduction

When designing a new industrial-scale furnace for the production of ferrochromium (FeCr), furnace operators have a choice between two operating philosophies: Submerged arc furnace (SAF) or open-arc furnace operations. The former typically applies an electrical system based on alternating current (AC) and the latter, direct current (DC). Choice in operating philosophy is primarily driven by the type of ore available [1]: SAF operation is dependent on lumpy raw materials (>6 mm) whilst DC open arc furnace operation was specifically developed for the reduction of fines (<6 mm) [2]. Another advantage of DC open arc furnace operation over conventional AC-SAF is the reduced dependence of process temperature on the electrical resistivity of the process material [3, 4]. Slag chemistry and process temperature can therefore be controlled independently to optimize activity of slag components

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participating in reduction reactions (improved recovery of Cr, low levels of S and P), manage slag viscosity for tappability, and in the case of an insulating lining design, manage activity of refractory components in the slag to minimize potential for refractory dissolution or chemical reaction between slag and refractory. Other advantages of DC open arc furnace operations over AC-SAF for FeCr production have been discussed extensively by others [2, 3, 5, 6].

Similarly, furnace operators have a choice between two furnace containment philosophies [7, 8]: Insulating or conductive lining designs (defined in the next section in terms of the steady-state heat-transfer principles applicable [9]). During the conceptual design phase the furnace containment philosophy needs to be selected with care as it will have a significant impact on future furnace operability. It is the intention of this chapter to demonstrate the use of desktop tools available to aid in the decision-making process during the conceptual design phase, and to discuss some of the consequences of the philosophy selected on plant design, commissioning, and operations.

Background

In pyrometallurgical processes, the input energy requirement (E_{In}) depends on two factors (see Eq. 1): Process energy requirement ($E_{Process}$) and energy losses from the furnace (E_{Losses}).

$$E_{In} = E_{Process} + E_{Losses} \quad (1)$$

The energy input, supplied in electric arc furnaces as electrical energy, is typically one of the operational cost drivers. The role of the refractory containment system therefore is not only to contain the process but also to minimize energy losses to the environment.

In an insulating lining, heat is transferred from the inside of the furnace to the environment through convective and conductive heat transfer mechanisms. Using an electrical analogy [8]—see Fig. 1a—for a one-dimensional heat transfer problem applied to a circular furnace (Eq. 2), the heat flux (Q, in $\mathrm{Wm^{-2}}$) is a function of the difference in temperature between the process material inside the furnace and the cooling medium acting as the external environment (T_{Liquid} and $T_{Coolant}$ respectively, measured in K), and the thermal resistances of the different components of the containment system as defined by the heat transfer mechanism applicable.

As an example, when heat is transferred from liquid slag to the hot face of the refractory layer through convection, the thermal resistance (R_{Liquid}) is dependent on the convective heat transfer coefficient (h, in $\mathrm{Wm^{-2}}$) of the slag and the radius of the hot face (r_i, in m) of the refractory, as defined in Eq. 3. Another example would be conduction of heat through the refractory: The thermal resistance ($R_{Refractory}$) is dependent on the thermal conductivity (k, in $\mathrm{Wm^{-1}K^{-1}}$) of the refractory and radius of the hot face and cold face (r_o, in m) of the refractory, as defined in Eq. 4.

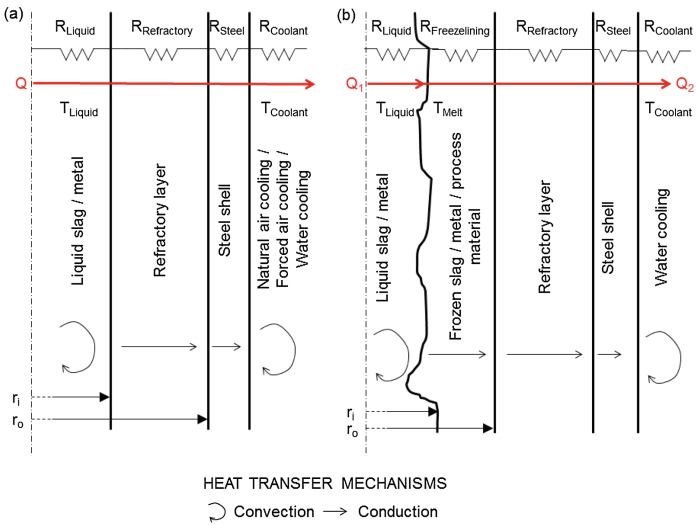

Fig. 1 Steady state heat transfer principles on which **a** insulating and **b** conductive lining designs are based

Descriptions of insulating lining designs, applied in FeCr production, were found for AC-SAF [10, 11] and DC-open arc furnace designs [12].

$$Q = \frac{T_{Liquid} - T_{Coolant}}{R_{Liquid} + R_{Refractory} + R_{Steel} + R_{Coolant}} \tag{2}$$

$$R_{Convection} = \frac{1}{2\pi r_i h} \tag{3}$$

$$R_{Conduction} = \frac{\ln \frac{r_o}{r_i}}{2\pi k} \tag{4}$$

In a conductive lining (Fig. 1b), furnace conditions are manipulated to ensure that a layer of slag, metal, or raw materials, or combinations thereof, are frozen on the hot face of the refractory [8]. A boundary condition is introduced to the heat transfer calculation: The temperature at which the frozen layer of process material starts to melt (T_{Melt}). Increasing the energy input to the process will result in melting the solid process material, reducing the thickness of the frozen layer without increasing the heat flux to the steel shell, therefore $Q_1 = Q_2$ (with Q_1 and Q_2 defined in Eqs. 5 and 6 respectively). Descriptions of conductive lining designs applied in FeCr production (albeit for significantly different refractory configurations), were found for AC-SAF [13, 14] as well as DC open arc furnace designs [6, 15–18].

$$Q_1 = \frac{T_{Liquid} - T_{Melt}}{R_{Liquid}} \tag{5}$$

$$Q_2 = \frac{T_{Melt} - T_{Coolant}}{R_{Freezelining} + R_{Refractory} + R_{Steel} + R_{Coolant}} \tag{6}$$

Although the intention with both design philosophies is to minimize energy losses to the environment, physical containment of the process is the most important consideration. In an insulating lining design, the hot face of the refractory material is exposed to liquid metal and/or slag. Chemical compatibility between the hot face refractory material and the liquid process materials is therefore important, thus adding an additional constraint in terms of slag conditioning. The refractory material should neither dissolve into, nor participate in, chemical reactions with process materials. In a conductive lining design the need for chemical compatibility between the hot face refractory material and the liquid process materials is greatly reduced. The potential for the process material to solidify on and attach mechanically to the surface of the refractory hot face is, however, important. The use of one-dimensional heat transfer, and thermodynamic and thermo-physical property calculations (utilising FactSage 7.0 software) [19] in selecting a suitable refractory containment system is illustrated in the next section.

Tools Available to Conduct Desktop Study

For the purpose of the discussion, a hypothetical case study was developed in which a producer of FeCr required the design of a furnace containment system for a new DC-open arc furnace. The calculations focus on the slag-line of the furnace—typically one of the high wear areas in a DC-open arc furnace [20]. Three slag compositions were evaluated (Table 1) selected from a range of compositions reported by Geldenhuys [1]. The selection was based on diversity in location of the ore body, and variation in bulk chemical composition of the slag.

The assumptions made for the one-dimensional steady-state heat transfer calculations are summarised in Fig. 2. T_{Melt} was estimated from the calculated percentage slag phase formed as a function of temperature, under equilibrium conditions. The Equilib module was applied, and FToxid and FactPS databases selected. All compound species were selected (gas, pure liquids, and pure solids),

Table 1 Three slag compositions (mass percent) evaluated in case study—after [1]

	Cr_2O_3	FeO	MgO	Al_2O_3	SiO_2	CaO	Total
Slag #1	3.8	2.1	31.3	33.7	28.0	1.1	100
Slag #2	4.3	3.4	16.7	37.2	22.9	15.6	100
Slag #3	6.2	1.4	43.8	19.1	28.8	0.7	100

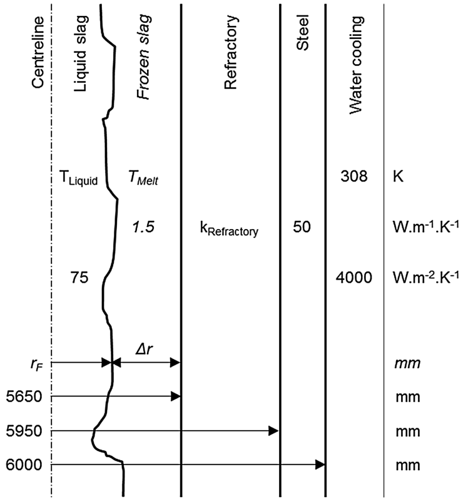

Fig. 2 Assumptions made for one-dimensional, steady-state heat transfer calculations where text in italics applied to conductive lining design calculations only

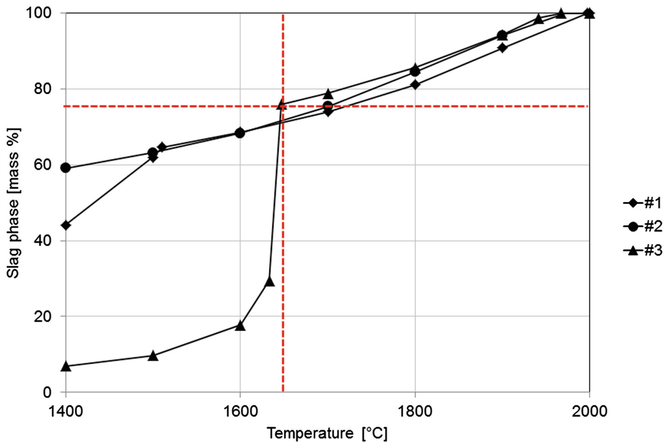

Fig. 3 Calculated equilibrium liquid phase formation in slags with compositions in Table 1 (*solid lines*) where the estimation of T_{Melt} estimation was based on the temperatures at which 80% slag phase formed (*broken lines*)

and duplicates were suppressed, with FToxid having preference over FactPS. All solution phases were selected except for B-olivine. The results are presented in Fig. 3. Wettability tests conducted on synthetic and industrial silicomanganese slag demonstrated that balling temperatures (considered to be the melting point of the slag) typically occurred in the temperature range where 80–95% of the slag phase is calculated to form [21]. Therefore, T_{Melt} was selected as the temperature where <80% slag phase formed: 1923 K (1650 °C). At lower temperatures, note the sensitivity of the slag phase formed for Slag #3, compared to Slag #1 and Slag #2 with changes in temperature.

Jones and Erwee [4] discussed ways in which slag compositions are designed for ferrochromium production, based on slag/metal separability (bulk liquidus) and tappability (viscosity). They stated that for ferrochromium slag to be tappable, the liquid viscosity—η_o—(calculated in the viscosity module of FactSage), should ideally be 0.2 Pa.s (2 poise) or less. Slag with a liquid viscosity of more than 0.45 Pa.s (4.5 poise) was considered not tappable. The Roscoe relationship [22] illustrates the effect of the volume fraction of solids (*f*) on the apparent viscosity (η_{app})—see Eq. 7.

$$\eta_{app} = \eta_o (1 - af)^{-n} \tag{7}$$

As illustrated in Fig. 4a, the apparent viscosity changes exponentially with the increase in the solids fraction. Therefore, assuming that a liquid viscosity of 0.2 Pa.s (2 poise) and solids mass fraction less than 10% are required for a tappable slag (see Fig. 4b, T_{liq} was assumed to be 2173 K (1900 °C). The typical tap temperatures for slag produced in a DC-open arc furnace, smelting South African ore—Slag #2 in Table 1—, is reported to be 1923 K (1650 °C) with bath temperatures of up to 1973 K (1700 °C) [15].

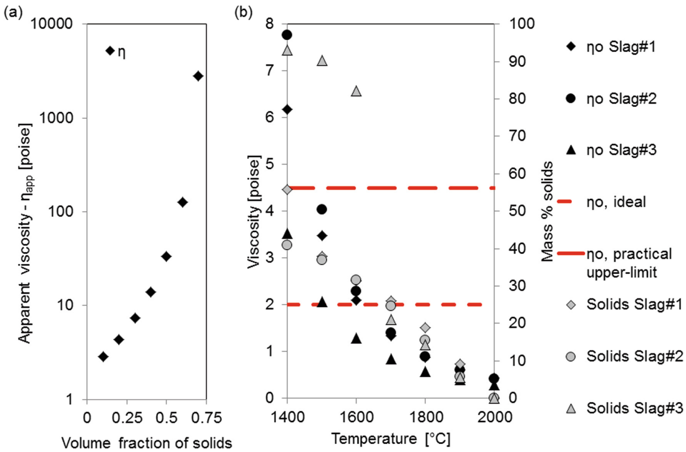

Fig. 4 **a** The effect of the volume fraction of solids on the apparent viscosity (η_{app})—estimated with the Roscoe relationship—as a function of temperature for the case where η_o = 2, a = 1.35, and n = 2.5. **b** On primary Y-axis: Calculated viscosity of the liquid portion of the slag (η_o) as a function of temperature, with ideal viscosity (similar to that of maple-syrup at 298 K (25 °C)) and the practical upper-limit for tappable slag [4] superimposed as *dash* and *long lines* respectively. On secondary Y-axis: Calculated mass per cent solids. Slag compositions were stated in Table 1

Table 2 Thermal conductivity ($k_{Refractory}$) of selection of refractory materials evaluated in case study as well as calculated radius of freeze lining (r_F), thickness of freeze lining (Δr), and heat flux (Q)

		$k_{Refractory}$ @ 1273 K (1000 °C) ($W.m^{-1}.K^{-1}$)	r_F (m)	Δr (mm)	Q (kW)
#A	Magnesia	4	5.631	18	663
#B	Sintered corundum	2.5	–	–	505
#C	Fireclay	1.4	–	–	297
#D	Spinel	2.5	–	–	505
#E	Carbon	10	5.565	85	656
#F	Graphite	80	5.527	123	651

Table 3 Composition (mass percent) of selection of refractory materials evaluated in case study—after [21, 23]

		C	FeO	MgO	Al_2O_3	SiO_2	CaO	Total
#A	Magnesia	–	0.4	97.9	0.4	0.3	1.0	100
#B	Sintered corundum	–	0.5	–	95.4	4.0	–	100
#C	Fireclay	–	2.7	–	22.1	75.2	–	100
#D	Spinel	–	0.9	29.9	67.7	1.0	0.5	100
#E	Carbon	90.2	–	–	9.8	–	–	100
#F	Graphite	100.0	–	–	–	–	–	100

For the insulating lining design, refractory material properties of interest are low thermal conductivity (Table 2) and chemical compatibility with the slag (Table 3), while for the conductive lining design high thermal conductivity is desirable. Magnesia-based [12, 15–18], and carbon-based [10, 13, 14] lining designs were found in literature, but Al_2O_3-, and SiO_2-based refractory were also evaluated for their lower thermal conductivity.

The results for the heat transfer calculations are summarised in Table 2: From the results of the one-dimensional steady-state heat transfer calculations (based on the assumptions discussed earlier), a solid layer of process material will only form for a magnesia or carbon-based lining design, not for the Al_2O_3-, and SiO_2-based refractory. Under these conditions, heat losses for the insulating lining designs are significantly (1½ to 2 times) lower than for the conductive designs i.e. an argument therefore exists for the selection of an insulating lining design.

To determine the chemical compatibility between the slag and oxide-based refractory material—as required for an insulating lining design—the equilibrium liquid phase formation when reacting 50 g of slag (compositions in Table 1) with 50 g of refractory (compositions in Table 3) was calculated. Although the calculation only applies to insulating lining designs, magnesia refractory was also included. The Equilib module was applied, and FToxid and FactPS databases selected. All compound species were selected (gas, pure liquids, and pure solids),

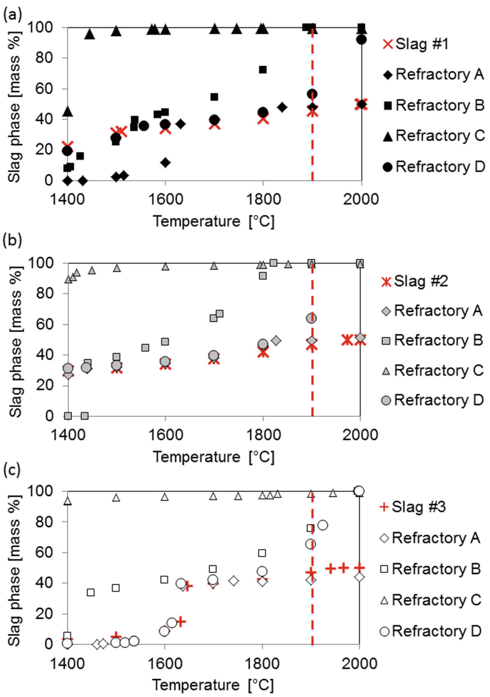

Fig. 5 Calculated equilibrium slag phase formation when reacting 50 g of slag (compositions in Table 1) with 50 g of refractory (compositions in Table 3) with equilibrium liquid phase formation in 50 g slag superimposed, for **a** Slag #1, **b** Slag #2, and **c** Slag #3, and the broken vertical *red-lines* indicate the typical tap temperature

and duplicates were suppressed, with FToxid having preference over FactPS. All solution phases were selected except for B-olivine, and mullite (FToxid-Mull). The results were presented in Fig. 5. Should the slag phase formation be less than or equal to the slag phase formation calculated for slag only, the refractory is considered compatible with slag. When more slag is formed it is not compatible with slag. From Fig. 5, refractory C is immediately excluded as the refractory will react with the slag. At the tapping temperature selected (2173 K (1900 °C)); refractory B and refractory D will also react with the slag. The only refractory suitable is refractory A. Therefore, even for an insulating lining design with slag in contact with refractory, magnesia-based refractory material at the hot face will be more suitable.

Consequences of Philosphy Selected

Irrespective of the furnace containment philosophy selected, slag composition and temperature need to be managed: For insulating lining designs, to ensure that the slag is saturated in the hot face refractory components; for conductive lining designs, to ensure that the slag freezes and remain frozen on the surface of the refractory. Managing the mass and the energy balance for the process is therefore important.

Referring back to Eq. 1: $E_{process}$ is recipe dependent (the enthalpy values of different raw materials differ), and is calculated by furnace operators in theoretical mass and energy balance calculations. The properties of importance in these calculations are masses, chemical compositions, temperatures, and enthalpies, of all inputs to and outputs from the furnace. Therefore, the following measurements on the plant are critical for process control:

1. Frequent, representative sampling of all input and output streams.
2. Accurate analyses, reported within a short time period from sampling (ideally within 30 min, but typically within 2 h for solid materials, and online analyses of off-gas), of all input and output streams.
3. Mass measurements (or volumetric flow measurements in the case of off-gas) of all input and output streams that are accurate, reliable, and validated.
4. Temperature measurements (especially for the output streams) that are accurate, reliable, and validated.
5. Enthalpy values of all input and output streams that are accurate and validated.

E_{losses} is calculated by furnace operators in energy loss calculations, based on water temperatures and flow rates for sections of the furnace that are water-cooled, and temperature differences in refractory material with known thermal conductivity for sections with no water-cooling. Therefore, the following accurate, reliable, and validated measurements on the plant are critical for process control:

1. Temperature measurements of water, at the inlet and outlet of cooling circuits.
2. Flow measurements of water, to or from, cooling circuits.
3. Temperature measurements in a single refractory brick, using dual thermocouples, where the exact positions of the two hot junctions are known.
4. Thermal conductivity of the single refractory brick, as a function of temperature.

These measurements should be included in the detailed design phase, taking into account not only how the systems will be managed during normal operation, but also how the systems will be checked and measurements validated during cold and hot commissioning of the plant.

A typical process control measure applied in DC-open arc furnace is the power-to-feed ratio, where power is the electrical energy input to the furnace and feed the total feed [16–18]. Typically, the furnace operator selects a specific power setting to operate at, and with known energy losses, adjusts the feed rate of the material fed to the furnace, in order to control the power-to-feed ratio for a specific recipe. At a constant power setting with constant energy losses, the power requirement will change when the recipe changes due to the differences in enthalpies of the input materials. The differences can occur when the ratios of feed materials change, e.g. ore/flux, or when the mineralogy of a specific feed material changes, e.g. changes in mineralogy within chromite ore.

If the energy requirement of the process changes without the awareness of the furnace operator, more or less energy can be added to the furnace than what is required by the process and energy losses—in layman's terms referred to as 'over-powering or under-powering the furnace'. In principle, the consequences of over-powering of the furnace are:

1. In open arc furnace operation, with an insulating lining design, the excess energy will increase the temperature of the slag saturated in refractory components (and metal, depending on the heat transfer mechanisms at play). An increase in slag temperature could potentially influence saturation of the slag in refractory components as illustrated in Fig. 5—an analogy would be when more sugar can be dissolved in boiled water compared to water at room temperature.
2. In open arc furnace operation, with a conductive lining design, the excess energy will melt away the freeze lining, but the metal and slag tap temperatures will remain essentially the same, until the freeze lining disappears. Thereafter, the heat transfer mechanisms essentially become similar to that of an insulating lining design with the risks of chemical incompatibility between refractory and process material, and temperature increases beyond the service temperature of the refractory material.
3. In SAF operation, the excess energy will allow for the burden to be consumed at a faster rate i.e. the production rate will increase (within the constraints of heat and mass transfer between the furnace slag bath and burden) and therefore the rate at which the furnace needs to be fed, but the metal and slag tap temperatures will remain essentially the same. Should the heat and mass transfer between the furnace slag bath and the burden become rate-limiting, the excess thermal energy will increase metal and slag temperatures resulting in the potential wear mechanisms described for open arc furnace operation.

Conclusion

In ferrochromium production, both insulating and conductive lining design philosophies are applied. Tools available for the evaluation of lining design philosophies at desktop level include the use of one-dimensional, steady-state heat transfer and thermodynamic and thermo-physical property calculations (utilising FactSage 7.0 software). Steady-state models tell only part of the story as insulating vs conductive linings have very different transient responses to disturbances in process conditions, which can affect the operability of the furnace significantly. Therefore the importance of further heat transfer modelling combined with laboratory and pilot-scale test work to validate the selection of lining philosophy as well as materials selected, cannot be over-emphasized. By not doing these tests on laboratory and pilot-scale, the industrial-scale furnace essentially becomes a pilot furnace. Once in operation, the power-to-feed ratio is one of the most important parameters to utilise for process control. It is therefore important to design for measurements that are accurate and reliable, and to validate these measurements during cold commissioning and hot commissioning of the industrial-scale furnace.

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