

Upgrading pilot-scale facility at MINTEK to evaluate the effect of pre-heating on smelter operations

Joalet Dalene Steenkamp, Glen Michael Denton, and Tertius Pieters

Abstract MINTEK in South Africa is investigating the effect of pre-heating on smelter operations mainly to reduce the electrical energy requirement for smelters. A pilot-scale facility is being developed which includes a one t/h rotary kiln coupled to an electric arc furnace (EAF) optionally served by either an alternating current (AC) or direct current (DC) power supply. The facility also includes integrated materials handling, product handling, and water-cooling systems. It allows for the evaluation of cold vs. hot feed (up to 900°C) on smelter operations over periods of 2–3 weeks continuous operation. The first application will study the effect of pre-heating on the smelting of titaniferous magnetite (15% TiO₂) using a DC-furnace as part of the TiMag project. The second application will evaluate the effect of pre-heating on the production of high carbon ferromanganese (targeting 78%Mn) using an AC-furnace as part of the PreMa project. The paper presents the results of the basic engineering of the project.

Keywords: pilot-scale, EAF, DC, AC, rotary kiln

1 Introduction

South Africa is resource rich, with large deposits of titaniferous magnetite and manganese amongst others. Titaniferous magnetite ore was smelted in the past to recover its iron and vanadium contents [1] and manganese ore for its manganese and

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iron contents [2]. Both of these processing routes are electrically energy intensive. Over the past 15 years, the average electricity tariff in South Africa has increased by more than 250% in real terms [3]. Extensive increases in tariffs were amongst the factors that culminated in the closure in 2016 of the only plant that smelted titaniferous magnetite ore and resulted in the mothballing of some of the manganese ore smelting facilities. The situation created the need for research into the possibility of reducing the electrical energy requirement of both processes by introducing a pre-heating step prior to smelting.

Mintek has over 45 years' experience in the research and development of titaniferous magnetite resources dating back to 1969. Overall, Mintek has conducted some 30 laboratory scale projects, several pilot-scale pre-reduction or smelting trials (1–10 ton), and five smelting campaigns at the 100 ton demonstration scale. Mintek developed and patented the DC arc smelting of both titaniferous magnetite and ilmenite with the latter being the first to be commercially implemented. While various process options have been technically proven, their economics are markedly less attractive without a pre-heating or pre-reduction step to optimise electrical energy consumption. Although ore pre-treatment itself is not a technical challenge, the direct coupling of pre-treated titaniferous ore to a DC arc furnace has not been demonstrated and there is still a risk perception which provides a barrier to commercialisation. Application for state funding to demonstrate the direct coupling of the two stages was successful and the TiMag project (2018–2022) was born.

High carbon ferromanganese (HCFeMn) is an alloy consisting of 74–82% Mn, 7.5% C, 1.2% Si, 8–16% Fe [5]. It is mainly produced in electric submerged arc furnaces (SAFs) through carbothermic reduction of manganese ores. The HCFeMn production process is energy intensive with requirements ranging between 2.0 and 3.5 MWh per ton alloy [6], [7], [8], [9]. The process is also a significant producer of CO₂ emissions, especially in countries where the electrical energy is supplied by coal-fired power stations i.e. South Africa. The PreMa project (2018–2022) aims at demonstrating a suite of innovative technologies to reduce the consumption of electrical energy and production of CO₂ emissions during the production of HCFeMn in SAFs. A pre-heating unit will be added to the flowsheet and various technologies are considered, the pilot-scales of which lie outside the scope of this paper. Included in the test program is a pilot-scale campaign, to be conducted at Mintek, where the effect of pre-heating ore to 600°C on SAF operation will be evaluated. Although special emphasis will be on the reduction of electrical energy consumption and production of CO₂, design and operational requirements of integrating a SAF with a pre-heating unit will also be studied.

In order to execute these two projects, the pilot facilities at Mintek are currently being upgraded. As a pre-heating unit, a one t/h, electrically heated rotary kiln will be coupled to an electric arc furnace (EAF) optionally served by either an alternating current (AC) or direct current (DC) power supply. The facility also includes integrated materials handling, product handling, and water-cooling systems. It allows for the evaluation of cold versus hot feed (up to 900°C) on smelter operations over periods of 2–3 weeks continuous operation. The choice of an electrically heated rotary kiln was

made for practical reasons and would not be the ideal solution at an industrial-scale when the aim is to "reduce the consumption of electricity".

The design phase of the pilot plant project is done in two stages: basic engineering followed by pilot-scale engineering of new equipment and structures as well as management of interfaces between existing and new systems. The paper presents the results of the basic engineering of the project.

2 Method

The method followed for the basic engineering study was as follows:

1. As a first step in the flowsheet design, the block flow diagram (BFD) was drawn to identify the function of each step in the flowsheet. Each function was then further described in the functional specification. No equipment pilot-scales were discussed.
2. In the second step, specific equipment was added to the flowsheet and material flows described in the process flow diagram (PFD) and process specification.

The purpose of the BFD is to represent the main processing sections in terms of functional blocks. Typically included in the BFD are the overall material balances and conditions at each state, where appropriate. The BFD basically summarizes the principal processing section and the functional specification describes the BFD in text [10].

The PFD provides a more pilot-scale view of the process. All major processing units in the process are displayed in the PFD as well as stream information and major control loops that will allow the process to be regulated under normal operating conditions [10]. Processing units are displayed using specific icons for each unit. Arcs or lines between the icons represent the process streams. Directed arcs, flowing from left to right wherever possible, represent the streams and are numbered for reference using a numbered circle. By convention, when lines cross, horizontal lines are shown as continuous arcs and vertical lines broken. Properties of each stream are provided in a separate table to be found in the process specification.

During the detailed engineering phase, the process control strategy will be described in the piping and instrumentation diagram (P&ID) and control specification. The P&ID transmits the process engineering design to the engineers responsible for plant construction. It is also used during start-up, process operation, and for operator training. It contains items that do not appear on the PFD i.e. the location and type of all measurement and control instrumentation, positioning of valves (including isolation and control), and the size, schedule, and materials of construction of piping [10]. Detailed engineering will therefore entail the final functional description, PFDs, equipment data sheets, P&IDs, mechanical, electrical and instrumentation, civil and structural design, and the final capital cost which includes construction on site.

3 Block flow diagram and functional specification

The BFD for the new facility is presented in Figure 1. What follows are the functional specifications for TiMag and PreMa.

Raw materials are received and cleared at the main gate (1). Raw materials are then dumped at the storage area for temporary storage (2). At the storage area, the materials are prepared by air-drying and manual bagging, if required (3). Once cold material is required at Bay 2, bags are transported from the storage area to Bay 2 where material is loaded into the feed system (4). Under cold feed conditions, all raw materials are fed directly into the smelter (8). Under hot feed conditions, material is first heated in the preheater (5). All raw materials are fed through the preheater for mixing as well as pre-heating purposes. Energy for heating of the raw materials is supplied to the preheater in the form of electricity (6). Hot material is fed (7) from the preheater into the smelter (8).

At the DC smelter (8), gangue minerals report to the liquid slag phase and a CO-rich off-gas forms during the reduction process. The smelter is operated in an open bath, open arc mode which means that the single, centrally located graphite electrode, is not in direct contact with the liquid slag and the energy input is transferred via a plasma arc jet. The energy required for the net endothermic reduction process, is provided in the form of electricity (9). The containment system is based on a conductive design philosophy. Cooling water is pumped from the water-cooling plant to the smelter for cooling of critical equipment (10). Hot water is returned (11) to the water-cooling plant for cooling (12). Molten slag (13.1) and iron (13.2) are tapped alternately from dedicated tap-holes, via oxygen lancing, into dedicated containers (14) where it is allowed to cool (15), and subsequently tipped in the storage area (16) from where both are disposed of (17).

At the AC smelter (8), the raw materials are choke-fed through the roof and reduced to form a liquid alloy phase which collects at the bottom of the smelter for the PreMa project. Gangue minerals report to the liquid slag phase. During the reduction process, a CO-rich off-gas forms. The smelter is operated in submerged arc mode which means that the electrode tips are in contact with a wet coke-bed that is again in contact with the liquid alloy. The wet coke-bed consists of carbonaceous reductant and slag. The energy required for the net endothermic reduction process, is provided in the form of electricity (9). The containment system is based on an insulating design philosophy. Cooling water is pumped from the water-cooling plant to the smelter for cooling of critical equipment. Hot water is returned (11) to the water-cooling plant for cooling (12). Liquid alloy and slag are both tapped from the AC smelter through a single tap-hole (13) into a container (14) where it is allowed to solidify and cool (15). Once cooled, the block is tipped in the storage area and the slag separated from the alloy (16). The slag and alloy are subsequently stored separately, from where both are disposed of (17).

For both furnaces, the off-gas formed is extracted and combusted to eliminate any CO or H₂ present (18). The hot, dust-laden, combusted off-gas is cooled and cleaned (19) with the clean gas subsequently vented to atmosphere (20) and the dust collected and stored (21) from where it is also disposed of (22).

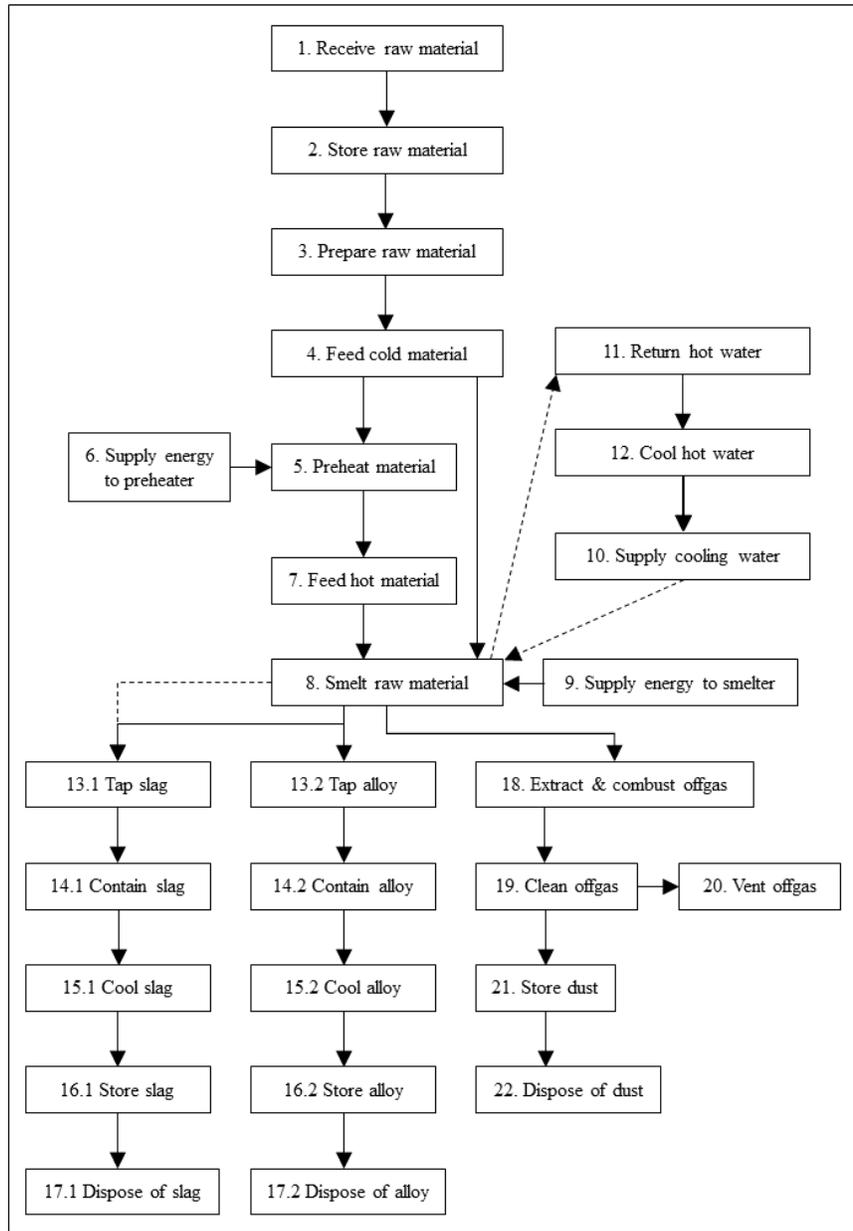


Fig. 1 Block flow diagram of the new facility

4 Process flow diagrams and general layouts

PFDs were drawn for both TiMag and PreMa, based on the BFD presented in 1. The PFDs are too extensive to include in this paper but an attempt was made to describe the process flow and equipment in the subsections presented here. It was only the rotary kiln, DC and AC furnaces, and their associated feed systems that had to be designed from scratch. The raw materials receiving and handling, slag and alloy handling, off-gas and dust handling, and water-cooling systems were already existing. The discussion that follows includes both existing and new equipment.

4.1 Raw materials receiving and handling

Raw materials are delivered by truck, either in bags or in bulk, and cleared at the main gate. Raw materials are then dumped at the storage area for temporary storage (Figure 2(a)). During storage of materials received in bulk, care is taken to identify each type of raw material to prevent confusion or mix-ups, to prevent contamination of raw materials by other raw materials i.e. leaves, etc., and to prevent contamination of the environment. If required, the materials are prepared by screening, air-drying (Figure 2(b)), and/or manual bagging (Figure 2(c)). Again, contamination of raw materials is prevented. Each bag is clearly marked to identify its contents. Bags are then stored in a covered area until further use (Figure 2(d)).

4.2 Feed system

When material is required at the plant, bags are transported by forklift from the storage area to Bay 2 where material is loaded by overhead crane into one of eight 1.5 m³ day bins. Each day bin is equipped with a grate at its inlet and a manual rod gate at its outlet. To prevent contamination, day bins are clearly marked as containing ore, reductant, and flux.

To prepare cold feed, raw materials are fed in batches from the four day bins positioned above the cold feed belt conveyor using electro-magnetic feeders. The bay bins are positioned on load cells should a blend of raw materials need to be prepared. The cold feed belt conveyor feeds raw materials into a bucket elevator which feeds into one of two 0.35 m³ surge bins. Material is directed via a flopper gate. Raw material is fed from surge bin into a loss-in-weight (LIW) feeder in batches by opening and closing the slide gate at the bottom of the surge bin.

To prepare hot feed, ore is fed in batches from the four day bins positioned above the hot feed belt conveyor using electro-magnetic feeders. The day bins are positioned on load cells should a blend of raw materials need to be prepared for pre-heating. The hot belt conveyor feeds raw materials into a bucket elevator which feeds into a 0.35 m³ surge bin. Raw material is fed from the surge bin into a LIW feeder in



Fig. 2 Examples of raw material handling in preparation for a campaign: (a) raw materials stored in bulk under tarpaulins to minimise contamination, (b) raw materials being air-dried in a covered area, (c) dried raw material being bagged in bulk bags, and (d) bulk bags clearly marked and stored in covered area

batches by opening and closing the slide gate at the bottom of the surge bin. The LIW feeder, with a bin capacity of 0.5 m^3 , continuously feeds the rotary kiln which pre-heats the raw material.

4.3 DC furnace

The rotary kiln continuously charges hot feed to the furnace, via a single feed chute and through a dedicated hot feed port located in the furnace roof. A gas seal, comprising a choke-fed screw, is incorporated in the feed chute design to prevent counter flow of furnace process gases. The LIW feeders, with a bin capacity of 0.5 m^3 , continuously feed cold material to the furnace, via a single feed chute, through a dedicated cold feed port located in the furnace roof. Electricity is supplied to the process via one graphite electrode, which enters the furnace through the roof, and a conductive hearth created by ramming refractory between steel pins. The electrode arm is operated hydraulically. Slag and iron are tapped alternately from dedicated, bi-level tap-holes.

The general arrangement of the feed system and DC furnace is presented in Figure 3. The design criteria on which the layout was based are summarised in Table 1.

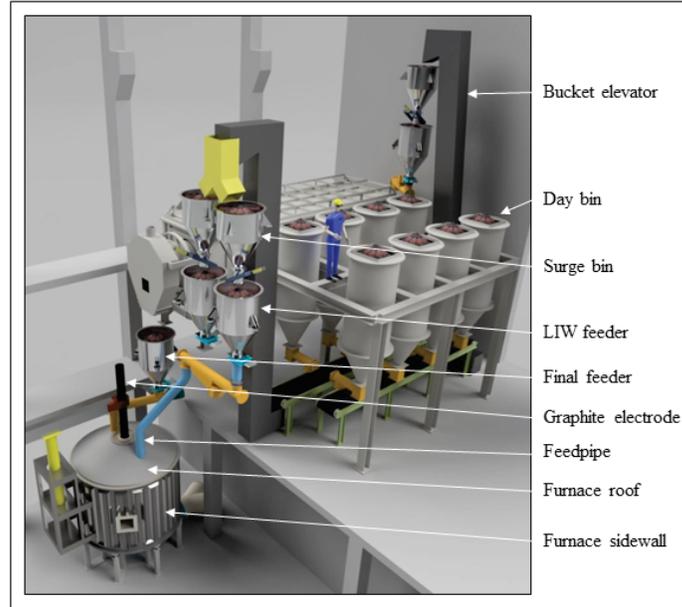


Fig. 3 Layout of DC furnace and associated feed system as per basic engineering design

Table 1 Design criteria for DC furnace and associated feed system

Parameter	Value	Unit
Process energy requirement (cold feed)	2.33	MWh/ton liquid iron
Process energy requirement (hot feed)	1.72	MWh/ton liquid iron
Maximum ore temperature	900	°C
Slag tap temperature	1700	°C
Iron tap temperature	1500	°C
Off-gas temperature	1700	°C
Process power input	1500	kW
Energy losses	30	%
Calculated feedrate cold ore	836 (max)	kg/h
Calculated feedrate cold anthracite	242 (max)	kg/h
Bulk density ore	2.5	ton/m ³
Bulk density anthracite	0.8	ton/m ³
Particle size range for all raw materials	1–12	mm
Hearth power density	500	kW/m ²
Shell power density	300	kW/m ²
Refractory inner diameter	2000	mm
Shell inner diameter	2468	mm
Shell refractory thickness	230	mm
Total external height (base to roof)	3000	mm
Electrode diameter	200	mm

4.4 AC furnace

The rotary kiln continuously feeds hot material via a chute into a mixing bin. The LIW feeder, with a bin capacity of 0.5 m^3 , continuously feeds cold material into the mixing bin. From the mixing bin, the raw materials are choke-fed into the AC furnace using a feed pipe with its outlet positioned at the furnace roof in the centre. This is done to ensure that the AC furnace is operated in SAF-mode. Electricity is supplied to the process via three equilateral-spaced graphite electrodes which enter the furnace through the roof. The electrode arms are operated hydraulically. Slag and alloy is tapped from a single, single tap-hole.

The general arrangement of the feed system and AC furnace is presented in Figure 4. The design criteria on which the layout was based are summarised in Table 2. The mass and energy balance calculations on which the criteria were based is reported in another paper submitted to the symposium.

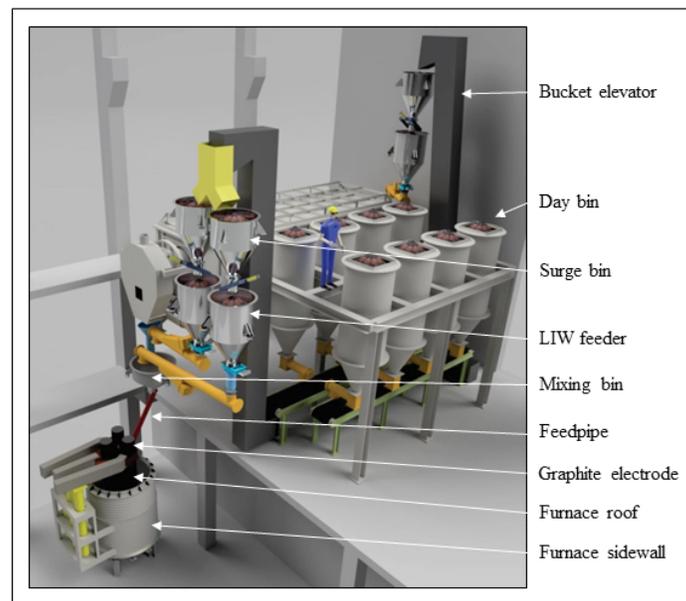


Fig. 4 Layout of AC furnace and associated feed system as per basic engineering design

Table 2 Design criteria for AC furnace and associated feed system

Parameter	Value	Unit
Process energy requirement (cold feed)	1.187	MWh/ton ore
Process energy requirement (cold feed)	2.304	MWh/ton alloy
Process power input	700	kW
Energy losses	50	%
Calculated feedrate Ore#A	202	kg/h
Calculated feedrate Ore#B	127	kg/h
Calculated feedrate coke	78	kg/h
Calculated feedrate quartz	76	kg/h
Bulk density Ore#A and Ore#B	2	ton/m ³
Bulk density coke	0.62	ton/m ³
Bulk density quartz	1.28	ton/m ³
Particle size range for all raw materials	6–20	mm
Angle of repose of mixture	42	degrees
Feed chute tip height below roof	100	mm
Electrode pitch circle diameter (PCD) power density	2 470	kW/m ²
Hearth power density	399	kW/m ²
Shell power density	300	kW/m ²
Electrode diameter	300	mm
PCD	601	mm
Refractory inner diameter	1496	mm
Shell inner diameter	1724	mm
Shell refractory thickness	114	mm
Distance from refractory to outside of electrode	297	mm
Height from bottom plate to tap-hole	380	mm
Height from tap-hole to top of sidewall	722	mm
Total height	1102	mm

4.5 Slag and alloy handling

At the DC smelter liquid slag or liquid alloy are tapped at different time intervals through bi-level tap-holes via a launder into a slagpot or into ladles stacked in series—see Figure 5.

At the AC smelter, liquid alloy and slag are tapped simultaneously through a single-level tap-hole via a launder and into ladles stacked in series—see Figure 6.

When the tap-hole is closed, the ladles or slagpots are transferred by forklift to the cooling area where the contents are allowed to solidify and cool. Once cooled, the ladles or slagpots are transferred to the slag waste area where the blocks are tipped and the slag separated manually from the alloy, should any slag be present in the ladle (see Figure 7(a)). The solidified and cooled contents of slagpots are also dumped in this area. The slag is stored in the slag waste area from where it is disposed of typically at a waste dump. The alloy is stored at the high value storage shed (see Figure 7(b)) and disposed of or sold.



Fig. 5 Typical ladle arrangement when tapping slag from a slag tap-hole and alloy from an alloy tap-hole in bi-level arrangement

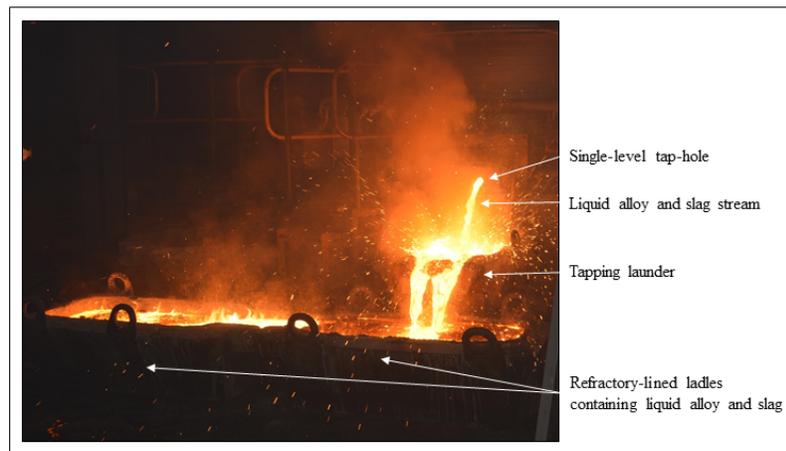


Fig. 6 Typical ladle arrangement when tapping alloy and slag from a single-level tap-hole

4.6 Off-gas and dust handling

For both furnaces, the off-gas formed is extracted via an off-take on the furnace roof and combusted at a slip-gap between the off-take and the off-gas stack to eliminate any CO or H₂ produced during the reduction process (see Figure 8).

The hot, dust-laden, combusted off-gas is cooled during transfer through a water-cooled duct and trombones. Dust is removed in a baghouse. The clean gas is subsequently vented to atmosphere via an off-gas stack. The dust is collected in bulk bags positioned below the baghouse and stored from where it is also disposed of typically at a waste dump. The off-gas fan is positioned between the baghouse and the stack.



Fig. 7 Typical examples of (a) slag and alloy being manually separated in the slag waste area and (b) alloy being stored in the high value shed

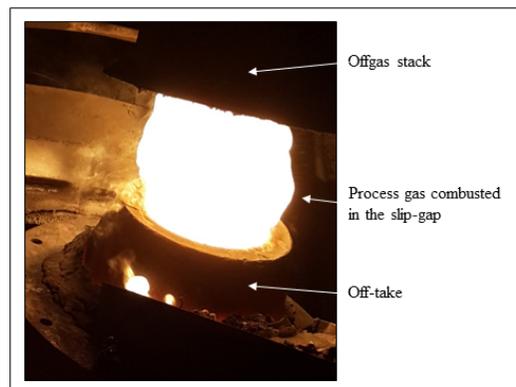


Fig. 8 Typical example of process off-gas being combusted at the slip-gap between the off-take at the furnace roof and the off-gas stack

An aerial view that includes the off-gas cleaning plant for Bay 2 is provided in Figure 9(b).

A secondary off-gas system, collects fugitive emissions at the raw material transfer points and the respective tap-holes. Dust removal takes place at a second baghouse, referred to as the environmental baghouse. Clean gas is vented to atmosphere via a stack and dust collected in bulk bags which are also stored and disposed of typically at a waste dump. Again, the off-gas fan is positioned between the baghouse and the stack.

4.7 Water-cooling system

For both furnaces, cooling water is pumped from the cold well at the water-cooling plant to the smelter for cooling of critical equipment. Water is pumped through a



Fig. 9 Aerial view of the bays and office blocks at Mintek from the North-Western side of campus. Bay 2 (a), the off-gas cleaning plant for Bay 2 (b), and the water-cooling plant for all of the pilot-scale facilities (c) are indicated

supply line to the main header from where it is distributed to the copper busbars and electrode clamps; sidewalls, roof panels, and tapblocks (should they require cooling); and the off-gas duct. Return water is collected in a tundish from where it is returned to the hot well at the water-cooling plant. Hot water is pumped from the hot well to cooling towers from where the cooled water is gravity fed into the cold well. Make-up water is received from the municipality and added to either the hot well or the cold well. An emergency water tank at Bay 2 can supply water to critical furnace components i.e. tap-hole blocks in cases where the main supply fails. The emergency tank is kept full at all times either by pumping water from the cold well or by supply with municipal water. An aerial view that includes the water-cooling plant for all of the pilot-scale facilities is provided in Figure 9(c).

5 Conclusions

A pilot-scale facility to evaluate the effect pre-heating of ore has one electric arc furnace operation is currently being developed at Mintek. The basic engineering of the facility was recently completed and the results were described in the paper. The BFD and functional specification described the flow of materials overall and identified the function of each step in the flowsheet. The PFD and process specification described the specific equipment utilised in the flowsheet. The design consist of a combination of existing and new equipment. Photographs were provided for existing equipment and general arrangement drawings for the new equipment. For the purpose of titan-

iferous magnetite smelting, a DC furnace was considered and for the production of high carbon ferromanganese, an AC furnace. As preheating unit, a rotary kiln was selected and included in the design of the feed system. Existing equipment included the raw materials receiving and handling, slag and alloy handling, off-gas and dust handling, and parts of the water-cooling circuits.

6 Next steps

The next steps will include (a) the pilot-scale engineering design of the facility and (b) the execution of the pilot-scale campaigns in 2020 for the TiMag project and 2021 for the PreMa project.

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