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THE DESIGN AND OPERATION OF TRANSFERRED-ARC PLASMA SYSTEMS FOR PYROMETALLURGICAL APPLICATIONS

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ABSTRACT

The current object of Mintek's plasma programme is to assist the pyrometallurgical industry in South Africa with the evaluation of thermal plasma technology. Research into the identification of the design criteria that affect the scale-up and operation of plasma units is being carried out. A 100 kVA d.c. transferred-arc facility was built and operated for study of the smelting and melting of ferro-alloys. Lack of knowledge of the mechanisms of stray arcing and energy transfer emerged as the major obstacles to the establishment of optimum design criteria.

1. INTRODUCTION

At Mintek it is considered that when compared with the submerged-arc furnace used for the production of ferro-alloys(1), plasma systems exhibit the following general advantages.

(1) The direct use of fine feed materials is possible.

(2) Independent control of feed rate and power can be achieved.

(3) The electrical conductivity of the materials does not limit input of power.

(4) Cost savings on electrodes can be realized.

(5) Higher power densities, and thus smaller reaction vessels, are probable.

A direct current (d.c.) transferred-plasma-arc approach was chosen instead of a non-transferred system for the following reasons:

(a) The use of an open bath of liquid slag and metal (the anode) permits greater control of the process metallurgy than with a choke-fed furnace.

(b) The electrical supply characteristics and geometric arrangement of the transferred-arc furnace are similar to the conventional submerged-arc furnace and the change to d.c. is relatively straightforward.

(c) Scale-up to industrial operation, when a graphite electrode is used, is now feasible.

(d) Transferred-arc devices have low cooling-water losses (usually less than 10 per cent).

The aim of this paper is briefly to discuss the operation of the 100 kVA facility and to examine the potential difficulties associated with scale-up of the transferred-arc system to a commercially viable size, e.g., 30 MW.

2. DESCRIPTION OF THE 100 kVA EXPERIMENTAL FURNACE

The equipment has evolved to a stage where continuous steady-state operation can be attained for several days. Therefore testwork can now be carried out primarily to investigate the process chemistry with only minor attention being required for the operation of the equipment. A diagram of the furnace is shown in Figure 1 and the equipment is described in the following six sections.

2.1. Furnace Shell

A cylindrical steel shell, 620 mm in diameter, was lined with a castable magnesia refractory to leave an inner volume of 57 litres, the taphole being positioned 100 mm above the hearth.

2.2. Anodes

Three stainless-steel rods (type 316), 40 mm in diameter, were embedded in the hearth 120° apart, to carry the current from the bath to air-cooled copper clamps. A permanent metal bath within the furnace completed the anode connections. Temperatures were measured centrally in each anode 15 mm inside the furnace shell by axially located thermocouples (type K).

2.3. Cathode

A hollow graphite electrode 50 mm in diameter, with a 10 mm bore, was used as the cathode, connected via a water-cooled clamp to the power supply and support frame. The electrode was suspended vertically in the centre of the furnace with sufficient hydraulically controlled movement to reach the anode for arc ignition. Provision was made for mixtures of argon and nitrogen to be passed down the centre bore at 5 to 50 ℓ/min to supply the plasma stabilizing gas. An arc of between 50 and 150 mm in length was usually employed, and over this range the arc column was typically 20 to 30 mm in diameter, stable, and vertical. The graphite electrode passed through a seal mounted on the furnace roof.

2.4. Roof and Electrode Seal

The roof consisted of a steel shell lined with carbon and backed with magnesia castable. Three ports were located in the roof, one centrally for the cathode, the other two peripherally to provide a feed and an off-gas port. Each port was lined with an alumina tube to protect the carbon from erosion. A water-cooled electrode seal provided a means of electrically isolating the cathode from the remainder of the furnace which was earthed for safety reasons. The seal was maintained by using two different types of refractory rings and a nitrogen gas purge.

2.5. Feed System

Two types of feed system were employed, a vibratory, and a screw-type feeder, which were sealed from the atmosphere right up to the furnace. The feed material in the hopper constituted the inlet gas seal, and this enabled the furnace to run under slightly positive pressure conditions. The feed materials were in the size range 0.2 to 6.0 mm and fed at various rates (5 to 70 kg/h) under gravity through the single feed port direct into the bath. No attempt was made to entrain the feed particles in the plasma-arc column.

2.6. Power Supply

A 104 kVA three-phase transformer provided with an on-load tap-changer (43 to 173 V) supplied power to three single-phase line reactors. A variable reactance can be selected and was usually 0.04 Ω in the range 0.01 to 0.64 Ω. A diode bridge arrangement provided full wave rectification. Typical operating values were 90 V, 800 A, and 72 kW measured across the cathode-anode busbars.

3. DISCUSSION OF THE OPERATION

The operation was aimed at the reaction of metal oxides in a liquid slag with a solid carbonaceous reducing agent in the bath of the furnace to yield a product metal.

3.1. Procedure

An initial arc was struck, and small amounts of a conductive metal were fed, which generated a molten pool under the cathode, followed by gradual heating (6 to 8 hours) at low power (20 to 30 kW) to bring the furnace up to a hearth temperature of about 1650°C. A 100 mm 'heel' of metal was established during this time by the addition of further metal. The power input was varied to establish steady-state conditions as determined by the lining thermocouples (Figure 1). The power required to maintain these conditions, although determined in the absence of feed, was assumed to be constant under feed conditions also. Therefore a straight-line relationship between available power and feed rate was established from a calculation of the energy requirements of the desired reactions using standard thermodynamic data at 1650°C.

The furnace was then fed continuously using the feed rate – power relationship determined, but with monitoring of the process for fine adjustments throughout, i.e., lining thermocouples, dip samples, visual observation, and dip thermocouple (Q.I.T.) measurements. Ideally, the bath should remain fluid, and be covered with a thin layer of reacting feed material throughout the feeding period, after which the feed should be stopped, final measurements should be made, and the furnace tapped, although a further period of treatment could be carried out if necessary.

3.2. Difficulties

The following problems encountered during the operation of the furnace resulted in significant improvements to the design.

(i) Anode burn-through. A rapid (less than 2 min) event leaving the refractory surrounding the anode almost intact. This resulted in three peripherally placed anodes replacing a central anode, but most important was the maintenance of a 50 to 100 mm metal heel at all times.

(ii) Stray arcing. Usually manifested by an increase in arc current without response to upward cathode movement. Apparently an additional current path consisting of cathode, carbon roof, steel shell, and anodes – earth is established. An extremely irregular event which could occur at any time in the operation but most likely with long (high voltage) arcs, high furnace-roof temperatures, and the absence of feed. The use of a well-designed electrode seal and adequate purge gas greatly minimized the frequency of these events which seldom caused appreciable damage when eliminated rapidly (i.e., in less than 2 min). The transformer was tapped down, the cathode was lowered, and occasionally the power was switched off briefly, to eliminate the stray arcing.

(iii) Roof damage. Overheating and collapse of the roof refractory was solved by the use of a carbon lining. This was feasible because of the highly reductive conditions maintained in the furnace for the process chemistry.

4. SCALE-UP

The success of this operation at 100 kVA scale for a number of ferro-alloy processes, and at 0.55 MW for ferrochromium(1) led to a consideration of the scale-up requirements for commercial implementation. The furnace efficiencies achieved previously (55 and 82 per cent at 70 kW and 550 kW respectively) led to the assumption that a direct scale-up to 10 MW or greater would yield comparable efficiencies to submerged-arc practice, i.e., about 92 per cent. The installation of a 20 MVA industrial unit(2) reflects confidence in the assumption.

The testwork was conducted at similar power densities (0.5 MW/m^2) to those of current submerged-arc practice(3), but the more constricted nature of a single d.c. plasma arc implies that much larger power densities are feasible. An examination of the scale-up problem in more detail is therefore of relevance. The two major areas of significance are the power supply and the furnace diameter which are discussed in the following sections for the specific case of ferrochromium at 30 MW scale.

4.1. Power Supply

The testwork done(1) defines the voltage range that can be used, e.g., 400 to 600 V which, in turn, fixes the current required, i.e., 75 to 50 kA. The choice of a single plasma device of this capability is limited at present to a graphite electrode in a similar arrangement to the 100 kVA furnace previously described. Water-cooled devices that would need to be employed in a multi-device configuration (which involves interactions between the arcs(4)), are not considered here. However, a single water-cooled device would place even fewer restrictions on the furnace geometry than a graphite electrode because of its smaller size and is effectively included in the discussion.

The voltage range chosen implies an arc length and thus defines a minimum bath-to-roof height. The influence of stray arcing suggests that the distance from the arc column to the walls and roof should be similar to the arc length to enhance a preferential electrical path via the bath.

4.2. Furnace Geometry

The arc length, and the type of plasma device, define some areas of the furnace geometry but the choice of furnace internal diameter can, in principle, be selected within wide limits. The conventional method(5) of scaling-up furnace diameters for submerged-arc practice is not applicable to a transferred-arc, single-electrode, open-bath situation, largely because this method depends on burden and slag-resistance paths that are not significant in the plasma furnace.

The relation between the internal diameter of the furnace and the power density (relative to the same diameter), at various power levels, is shown in Figure 2. Conventional submerged-arc practice typically utilizes a power density of 0.5 MW/m^2 but preliminary observation of the 100 kVA furnace operating at greater than 1 MW/m^2 suggests that in an open-bath system much higher power densities could be utilized. The potential advantages of employing power densities of 1.5 to 2.0 MW/m^2 are substantial as can be seen from Figure 2, and imply a reduction in diameter from 9 to 5 m at 30 MW.

The limitations of employing such power densities are likely to be

(i) chemical reaction rates, or

(ii) energy transfer rates.

The chemical reaction rates were observed as extremely rapid(1) and could be further improved with stirring, better feed distribution, and bath-injection techniques. The effect of power densities upon the energy transfer rates, however, remains an unknown quantity because of a lack of knowledge of the energy-transfer mechanism from a plasma-arc column to the bath, roof, and side walls of a hot furnace.

5. CONCLUSIONS

5.1. The 100 kVA furnace demonstrated the advantages of transferred-arc plasma processing for ferro-alloys, particularly the metallurgical control, at similar power densities to those used in submerged-arc furnaces.

5.2. The scale-up of these plasma furnaces to 30 MW at similar power densities, with adequate efficiencies, appears feasible, but it is evident that considerable scope exists for improving scale-up by the employment of higher power densities.

5.3. The attainment of these high power densities is at present limited by a lack of understanding of the mechanisms of stray arcing and energy transfer.

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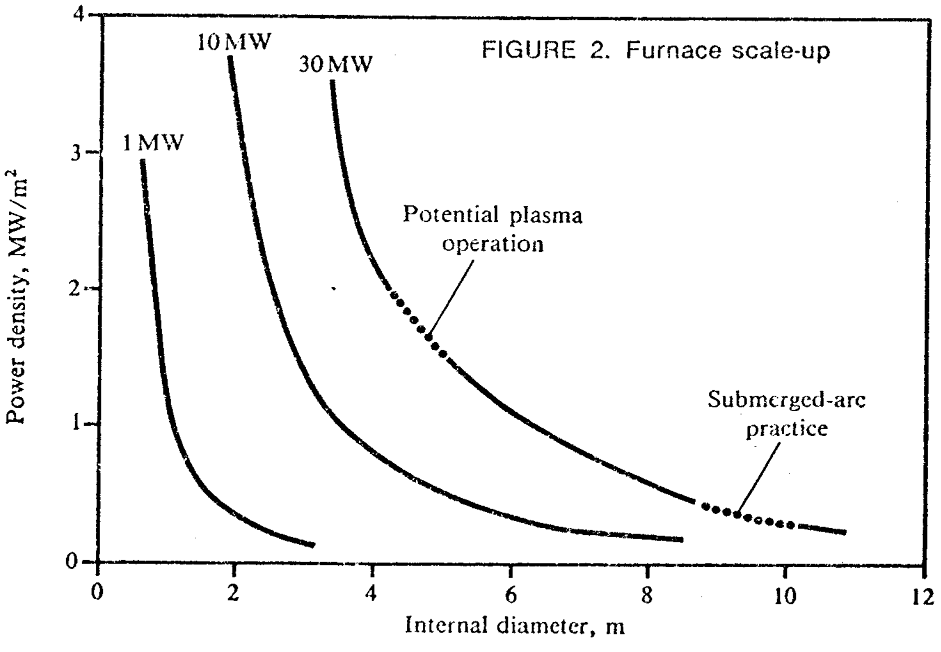
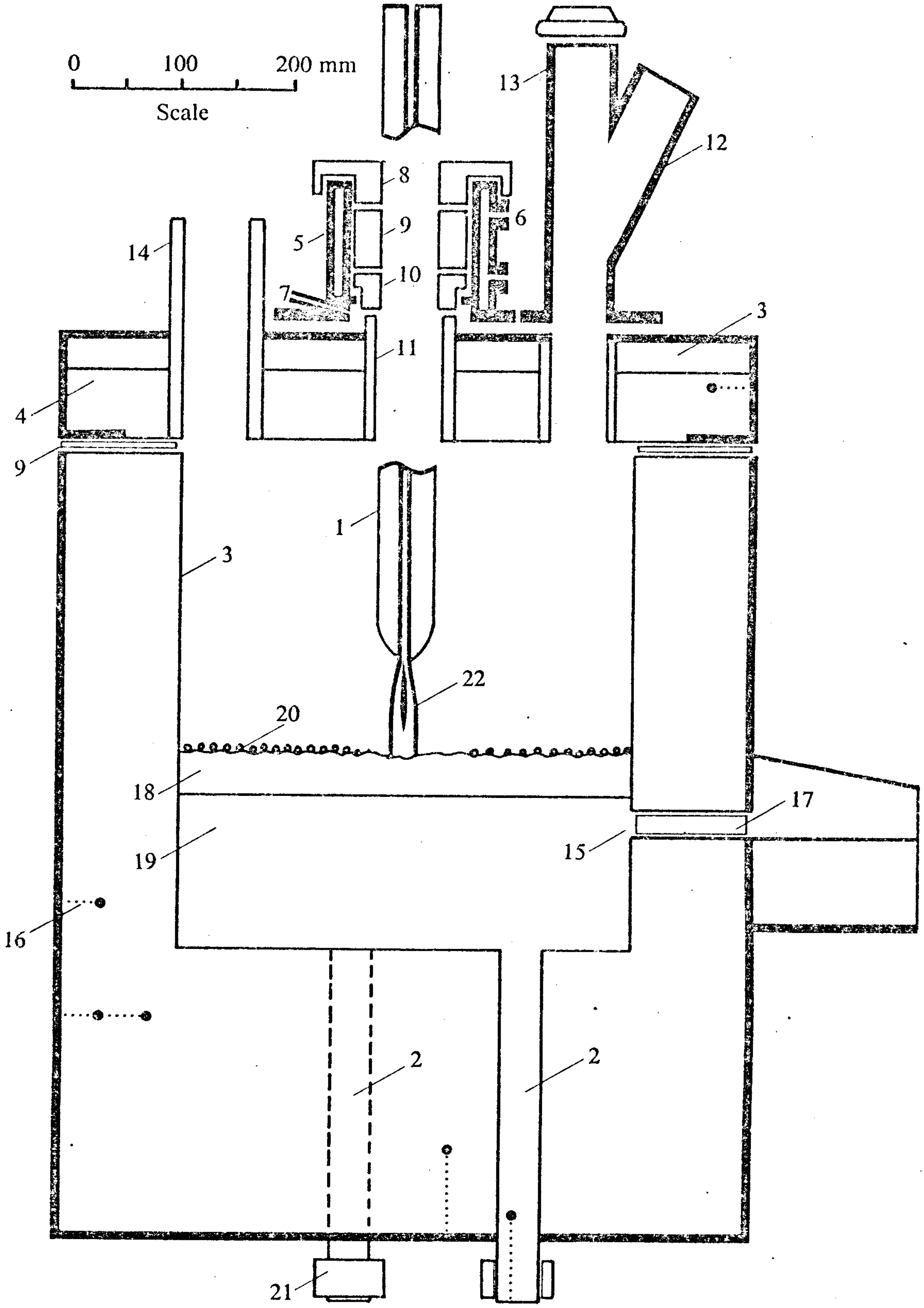


FIGURE 2. Furnace scale-up



1 central cathode 2 anode 3 magnesia refractory lining 4 carbon lining 5 electrode seal 6 water cooling 7 nitrogen purge 8 ceramic ring 9 alumina wool 10 alumina ring 11 alumina tube 12 feed port 13 access port 14 gas offtake, alumina 15 taphole 16 thermocouples 17 clay plug 18 slag layer 19 metal 20 unreacted feed 21 anode clamp 22 plasma zone

FIGURE 1. Arrangement of the 100 kVA transferred-arc plasma furnace