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by

T.R. Curr
K.U. Maske
K.C. Nicol

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T.R. Curr, K.U. Maske, and K.C. Nicol
Council for Mineral Technology
Private Bag X3015, Randburg 2125, South Africa.

ABSTRACT

The factors influencing a smelting operation at high power densities in a transferred-arc plasma furnace are evaluated. A continuous test indicated that an increase in the power density from 0,35 to 0,80 MW m^{-2} increased the furnace efficiency from 15 to 69 per cent because the energy losses remained constant with increased feed rates. However, still higher rates led to unstable furnace operation, probably because the reaction rates on the bath surface became limiting.

1. INTRODUCTION

The Council for Mineral Technology (Mintek) has been involved in research-and-development work on the application of thermal plasma since 1976[1]. For the past 6 years that has entailed an active evaluation of transferred-arc open-bath plasma systems in remelting and smelting applications pertinent to the South African pyrometallurgical industry. The comprehensive pilot-plant facilities that have been established at Mintek permit experiments to be conducted at power levels from 30 kW up to about 2 MW in a range of furnaces with internal diameters of 0,2 to 1,5 m. These facilities have been described in detail elsewhere [2-4].

Most of the work at Mintek has been directed towards materials of relatively low value, e.g. ferro-alloys, iron, steel, and stainless steel, because of the abundance of the associated minerals in South Africa. The attainment of large-scale plasma systems capable of processing these materials at a throughput large enough to be economical, therefore, is of particular interest to Mintek. Although such open-bath systems have been applied to remelting, their application as smelting systems has been hampered by the increased complexity involved in the interfacing of the chemical reduction reactions with the plasma arc[5].

2. ASSESSMENT OF REQUIREMENTS

A previous study[2] has indicated that there is considerable scope for improvement of the existing submerged-arc furnace by its conversion to a transferred-arc furnace, in which it might be possible for the overall power density (power per unit of hearth area) to be increased from 0,5 to 1,5 MW m^{-2}. This would have the advantage that a substantial increase in furnace throughput would be achieved.

Some of the factors that may limit this increase were considered in the present investigation.

2.1 *Reaction rates and mechanisms*

The smelting processes considered were the open-bath carbothermic reduction of metal oxides in the presence of a silicate slag.

The following reaction sequence is envisaged;

(i) dissolution of the metal oxide into the slag phase at the surface and within the bath,

(ii) the reaction of dissolved metal oxide with solid carbon at the slag surface,

(iii) the descent of the metal droplets formed through the bulk slag phase,

(iv) further reaction (i.e. refining) of these metal droplets with the slag while they are descending to the bulk metal phase, and

(v) the final approach to equilibrium at the interface between the bulk slag and the metal.

As the feed flux (i.e. the feed rate per unit hearth area) increases, the most probable rate-limiting step should be (i) or (ii), since they occur at the surface of the liquid slag bath. An accumulation of feed material would be expected in either case, and undesirable side reactions might occur, leading to unsatisfactory metallurgical performance.

2.2 *Interfacing of the plasma arc with the bath*

A well-directed arc with its attachment in the centre of the bath is required to convey the energy generated in the arc to the metallurgical reactions in an efficient manner, since any skewing of the arc may cause very severe damage to the refractories. This requirement is more critical if the arc power is increased or the furnace diameter is reduced in an attempt to increase the overall power density. Various factors affect the maintenance of a centralized arc, which behaves as a uniform heat source under different operating conditions. These have been discussed in depth[6], and are briefly reviewed below.

(a) The arc current is an important parameter because of its influence on the cathode jet. The required arc power is obtained preferably by maximization of the current and minimization of the voltage. At higher currents, a centralized arc is readily achieved.

(b) The design and shape of the cathode is a very useful parameter in centralizing of the arc where there are constraints resulting from the power supply.

(c) The composition and velocity of the stabilizing gas also has a significant effect.

(d) The arc length requires constant attention during an experiment. Although a considerable jet is induced in the cathode, its motion is retarded along the length of the arc via mechanisms like natural convection, energy extraction, or opposing flow fields. For example, a forced increase in the arc length to increase the power input via an increased voltage can cause skewing of the arc and subsequent damage to the refractories or a change in the characteristics of the thermal-energy source.

2.3 *Introduction of feed materials to the bath*

Quite clearly, there is a possibility that localized imbalances will occur on the surface of the bath upon the introduction of cold unreacted feed materials. If, for example, excessive feed should arrive in an area of the bath, causing local cooling, this feed and any new feed arriving in the same area would not attain the reaction temperature. Since the input energy would not be used by this feed, localized overheating would occur in a different region of the furnace. Hence, an increase in the feed flux might cause difficulties in several areas of the feeding equipment, as follows.

(i) The segregation of the raw materials in the feed hopper could cause periodic imbalances in the recipe with subsequent imbalances in the energy requirements. For this reason, each raw material should be fed through a separate hopper-feeder arrangement.

(ii) The rate at which the feed is delivered into the furnace needs to be controlled within very close limits, since surges in the feed rate could induce local cooling.

(iii) Unfortunately, the number of feed ports that can be used are subject to practical restrictions, especially in furnaces of smaller diameter.

2.4 *Furnace configuration*

The design of the furnace configuration is affected by increased power densities via the method by which the power is supplied, the energy losses, and the flowrates of the products. At its simplest, the attainment of higher power levels can be regarded as an increase in the operating current or voltage. The higher-current option requires that an increased electrode current density or larger electrode diameter is used. This affects the rate of electrode consumption and the ratio of the electrode diameter to the internal diameter of the furnace. (From Mintek's experience, this ratio should be less than 0,2.) The higher-voltage route requires a longer arc length or an increased arc resistivity. This has consequences for the directional stability of the arc, and the distance from the bath to the roof.

The energy losses will depend upon the temperature distribution in the furnace at the higher power density. The possible changes in this distribution will depend on the technique by which the power is increased. The exact effects cannot be predicted accurately, and pilot-plant tests are required for the determination of the most suitable refractory configuration, e.g. water-cooled roof panels. The high throughput rates for the feed materials, which would result from high power densities, should allow water-cooling to be used extensively without a decrease in the efficiency of the furnace.

The increased production rates of liquid furnace products (slag and metal) require a decreased tap-to-tap time and, at very high power densities, may involve continuous tapping. The gas volumes produced may limit the minimum particle sizes of the feed materials owing to the risk of entrainment, since the superficial gas velocity in the furnace rises with increasing reaction rates at increased power densities.

2.5 *Process control*

No reliable, direct, and continuous means for the measurement of the average temperature of the bulk slag or metal has been developed for the open-bath furnace. Hence, considerable emphasis is placed upon the balance between the feed rate and the power level as a means of process control. This approach allows a reasonably steady-state condition to be established so that the desired product can be produced, but variations in the ratio of the feed rate to the power level will cause deviations from steady-state conditions. At higher power densities, these imbalances are more critical, so more stringent control is required.

3. FURNACE TRIAL

A test campaign was carried out over a period of 5 days, the objective being the attainment of the maximum possible power density and measurement of the corresponding furnace efficiency for a carbothermic smelting process with a thermodynamic-energy requirement of 1 kW.h per kilogram of feed.

3.1 *Experimental*

The furnace configuration used is depicted in Figure 1, and differs from the previously described furnace configuration[2] primarily in the anode arrangement, the roof-to-wall seal, and the power supply. A distributed-anode arrangement was used with indirect electrical connections to minimize the possibility of a metal 'break-out' via the anode[7]. The roof-to-wall electrical insulation was increased to reduce the probability of 'stray arcing' from the furnace roof, which was at a floating electrical potential to the earthed steel shell.

Control of the feed rate was achieved by the use of a multiple hopper system, each hopper being equipped with a vibratory feeder and an integrating controller. These controllers ensured a constant feed rate from 2 to over 200 kg h^{-1}, as well as a constant feed composition at all times.

A thyristor-based d.c. power supply was used for the control of power to the furnace. The power set point was selected by the operator, and a programmable logic controller (PLC) was used to control the thyristors by varying the set point of the current to compensate for variations in the arc voltage.

All the on-line data from the furnace were monitored by a data logger that was capable of processing the data and displaying them to the operator, who could adjust the set points for the power level and the feed rate, if necessary.

3.2 *Results*

It was found that erosion of the refractory side walls took place during the first eight taps, after which a stable lining condition was established, as determined by the slag composition. The internal diameter of the furnace at the slag line was measured after the campaign and found to be 0,52 m; this value was used for the calculation of the power densities of all the subsequent taps. The power density was increased in stages from 0,47 to 0,94 MW m^{-2} during taps 9 to 17. The feed rate was increased from 96 to 156 kg h^{-1}, and a maximum furnace efficiency* of 78 per cent was attained. However, this operation could not be sustained, since the metallurgical performance declined sharply and furnace eruptions were encountered. A series of 21 taps at 0,80 MW m^{-2} and 117 kg h^{-1} were then carried out so that steady-state conditions could be established. A furnace efficiency of 69 per cent resulted. During the subsequent 14 taps, power densities of 0,95 to 1,04 MW m^{-2} were achieved, but only at reduced feed rates and, consequently, lower efficiencies.

*Furnace efficiency = 100 x (feed rate, kg h^{-1} x thermodynamic requirement, kW.h kg^{-1}) ÷ actual power, kW.

These results are shown in Figure 2. The measured energy losses through the roof and side walls remained fairly constant (52 ± 3 kW) at all power densities once the initial period of refractory erosion had taken place.

The feed rate appeared to be limiting, at 117 kg h^{-1} (or 550 kg h^{-1} per square metre of hearth area), rather than the power density. The metallurgical performance declined at higher feed rates, whereas operation at higher power levels was possible. However, this operation was not attractive because of the lower furnace efficiencies that resulted (60 per cent).

4. CONCLUSIONS

The carbothermic reduction of a metal oxide has been demonstrated at a feed rate of 117 kg h^{-1} and a power density of 0,8 MW m^{-2} in an open-bath transferred-arc plasma furnace with a furnace efficiency of 69 per cent.

The energy losses from the furnace remained relatively constant at 52 ± 3 kW over power densities ranging from 0,35 to 0,80 MW m^{-2}, which accounted for the increased furnace efficiency from 15 to 69 per cent.

Unstable operation and poor metallurgical performance resulted if feed rates higher than 120 kg h^{-1} were sustained for longer than two taps. This was interpreted as being due to limited reaction rates at the surface of the bath.

Further work in this area will be aimed at the overcoming of these limitations by the use of finer feed materials, agitation of the slag and metal bath, and direct injection of the feed into the bath, which will allow still higher power densities to be attained at comparable or increased furnace efficiencies.

5. ACKOWLEDGEMENTS

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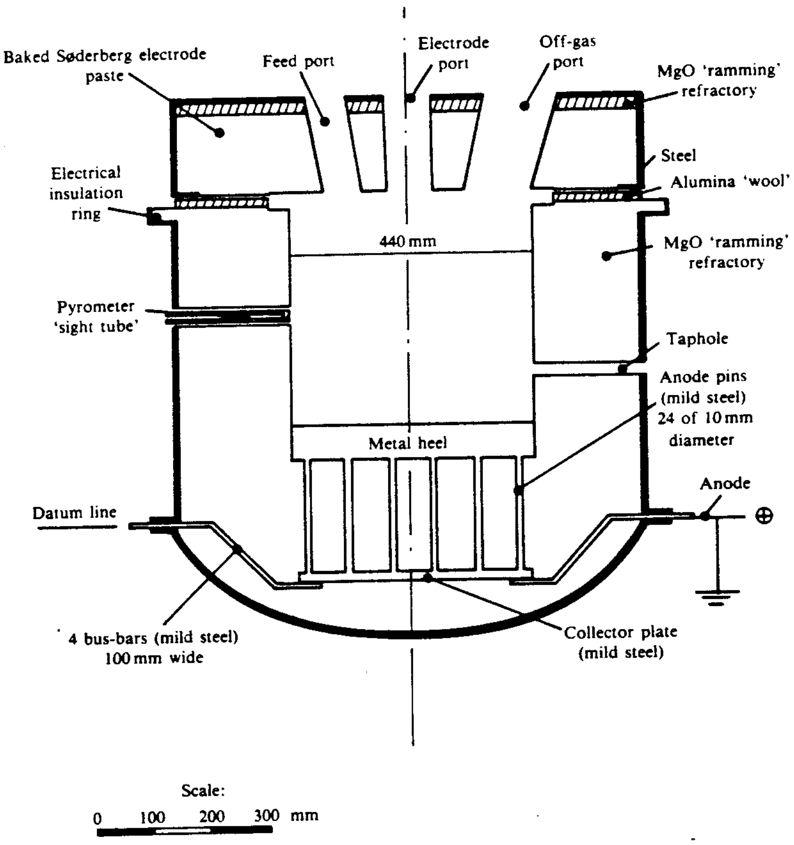

FIGURE 1. The furnace construction

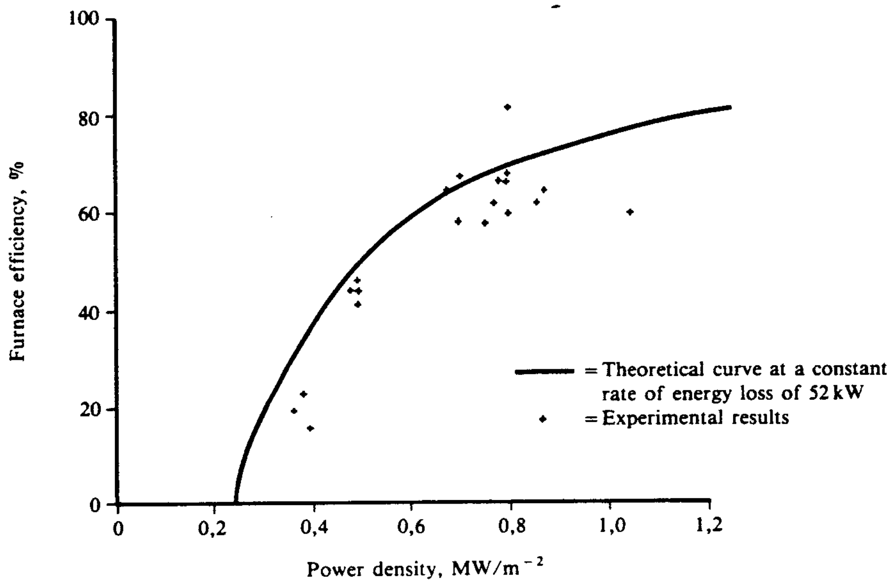

FIGURE 2. Comparison of theoretical and experimental values for power density versus furnace efficiency