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TITLE OF THE PAPER:

The Control and Operation of a Pilot-Plant d.c. Plasma Furnace

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Abstract

The single-electrode d.c. plasma-arc furnace can be used to replace the conventional submerged-arc furnace for the production of ferro-alloys.

The major advantages of the plasma furnace are: the ability to process fine material directly, a high degree of flexibility in the choice of raw materials, improved efficiency of reduction, and the use of a smaller furnace with only one electrode to give the equivalent power level.

However, for consistent stable metallurgical performance, the plasma furnace requires a high degree of control, the major aspects of which are: the feed rate of raw materials, the input of electrical power, and the setting of the ratio of the feed rate of the raw materials to the power input.

This paper describes the manner in which this has been achieved on pilot-plant facilities at the 200 to 300kW and 1.2MW levels.

K.C. Nicol, M.S. Rennie, A.B. Stewart

In conventional submerged-arc furnaces for the production of ferro-alloys, the raw materials descend under gravity into the reaction zones beneath the electrodes. The successful operation and control of these furnaces depend upon careful selection and sizing of the raw materials, and control of the electrode-tip position and power input in each phase. The furnace responds slowly to changes, and there is little flexibility or control of the feed rate and the distribution of the raw materials in the feed. The power regime under which the furnace can operate is limited not only by the characteristics of the transformer but by the size of the furnace shell, the diameter of the electrode, and the characteristics of the feed materials. In contrast, the open-bath operation of the d.c. plasma furnace allows for a high degree of flexibility. This furnace can process raw materials of a wide range of particle sizes and different physicochemical characteristics, it can use widely varying levels of operating power, and it allows the feed rate of the raw materials to be varied independently to produce a specific material.

The penalty for this flexibility of operation is the need for a much higher level of process control than is currently required in the operation of submerged arc furnaces.

In 1980 the Council for Mineral Technology (Mintek) decided to install a pilot plant test facility to develop

the application of plasma technology to the production of ferro-alloys⁽¹⁾. Although the potential advantages offered by d.c. plasma furnaces were recognized⁽²⁾, it was perceived that a test facility of reasonable size would be needed to demonstrate these advantages to the ferro-alloy industry at an acceptable scale. During the early stages, water-cooled transferred-arc plasma torches were employed, but it soon became apparent that these devices offered limited scale-up capability. Further work using graphite electrodes showed that most of the advantages of d.c. plasma operation could be realized with this much simpler arrangement, and that scale up to operation at more than 100kVA was possible.

The Mintek pilot plant facility developed over a number of years from a small 100kVA facility performing mainly pot-test types of experiments to a large-scale 3.2MVA facility capable of sustained operation at power levels greater than 1MW. Figure 1 shows the major features of the facility. The power supply for the large facility was selected to provide a high degree of flexibility, and consists of two phase-controlled d.c. supplies (1800A, 750V) capable of operating in series, in parallel, or as separate systems. One of the power supplies was used for a 200 to 300KW furnace (nominally called the 200 kVA facility) that was located adjacent to the large furnace for testwork on the intermediate level.

K.C. Nicol, M.S. Rennie, A.B. Stewart

This proved to be an extremely important stepping stone for scale up from the 100kVA (60kW) to the 3.2MVA (1.2MW) level, since operational problems could be solved at a relatively low cost.

In the operation of the furnace at 200 to 300KW, it was extremely difficult to obtain consistent repeatable results owing to the short time constants associated with the process, the necessity for the feed of raw materials to be placed at the desired rate in the correct part of the furnace close to the arc, and the necessity for a wide range of variables to be controlled and monitored. These problems resulted in poor metallurgical performance during early campaigns on this facility, and it was only after a comprehensive data acquisition and control infrastructure had been set up that consistent, stable operation over many days could be achieved. With the infrastructure it also proved possible for the larger 3.2MVA facility to achieve the same (and possibly better) level of performance over many weeks.

This process-control environment has many aspects, and all these factors contribute to the overall performance of the furnace. However, the most important factor has proved to be the continuous control of the ratio of the feed rate of the raw materials to the power input. This ratio is not a constant, and has to be regularly updated as furnace conditions change. However, before these factors are

considered it is necessary to discuss the two major primary-control variables, viz control of the feed rate of the raw materials and control of the power input.

Feeding Problems

Existing submerged arc furnace technology involves gravity feeding of the raw materials into the reaction zone. This is a self-regulating system because, as the burden in the vicinity of the electrodes melts, the molten material is replaced by raw materials, and the electrodes move so that the desired electrical setpoints are maintained. In normal furnace operation, therefore, there is no need for the continuous determination or measurement of the amounts of the various materials fed to the furnace. This closed bath operation also means that the gas generated is contained in the burden, and a significant amount of the energy contained in this off-gas stream is transferred to the burden. Also the refractories on the walls and the roof are protected from the gas and the arc flare by the burden.

In contrast, the open-bath configuration of a plasma furnace requires new methods of feeding and feed control. The plasma-arc energy must be efficiently utilized, the refractories must be protected, and a reducing atmosphere must be maintained so that the ore will be reduced and oxidation of the electrodes avoided.

K.C. Nicol, M.S. Rennie, A.B. Stewart

This means that a gas-tight feeding system is required. Sealed vibrating-pan feeders are therefore used, the material above the pan acting as the gas seal. The feed rate must be accurately controlled if steady state conditions are to be obtained in the furnace. Essentially an attempt is made to keep the temperature of the bath constant by the supply of enough energy to promote the metallurgical process and to compensate for heat losses.

For the furnace to produce products to specification, it is also necessary to ensure that the proportions of the components of the feed are closely controlled throughout a batch and that little or no segregation occurs. Deviations from the design recipe can result in unwanted metallurgical reactions that will change the total energy balance.

A multiple-hopper system is used to avoid segregation of the feed, ie each feed component is contained in a separate hopper, which is equipped with a vibrating-pan feeder and mounted on load cells. The arrangement is shown in Figure 2. A novel integral feed rate controller was designed to control the feed rate of the various components. This controller is based on the integral approach in which the voltage of the loadcell (i.e. the mass of the hopper) is forced to follow a ramp generated by an accurate digital ramp generator. The slope of this ramp is determined from the set point of the feed rate.

This controller is far more stable than the conventional mass loss technique usually employed by industrial weigh feeders. In addition, the controller has the advantage that because of its integral nature, its overall immunity to noise from electrical and mechanical sources is far greater. An additional feature of the controller allows one of the feeders to act as a 'master' controller while all the other feeders are ratioed to this master. This ensures very accurate control of the proportions of the different feed materials at all times.

The Feed of the Raw Materials into the Furnace

The design of the system to feed the raw materials into the reaction zone of the furnace must take a number of factors into account.

The most important of these is the necessity for the feed to be placed in the hot molten reaction zone generated by the arc, since this ensures adequate dissolution of the raw materials and hence efficient reduction of the metal oxides to metallic form. There is a steep drop in temperature away from the arc zone and therefore it is necessary to locate the feed pipes as close to the electrode as possible. It is also necessary to distribute the feed pipes around the electrode and thus ensure the presence of a 'curtain' of feed around the electrode to shield the arc. Any material that does not

K.C. Nicol, M.S. Rennie, A.B. Stewart

dissolve adequately in the molten bath usually reports to the slag in non-reduced form, and the efficiency of reduction is consequently poor.

The correct feeding arrangement has enabled plasma furnaces to achieve higher reduction efficiencies than conventional submerged-arc furnaces can achieve. The reason for this is that, in the operation of a submerged arc furnace, it is not possible to ensure that ore and reductant are present in the correct proportions and at sufficiently high temperature for efficient reduction to occur.

Another important factor to be considered in the feeding of raw materials into a plasma furnace is the need for feeding to continue whenever power is on. The introduction of the feed into the furnace results in a significant increase in the voltage gradient. This means that, for a given power and current, a shorter arc is possible, resulting in more efficient heat transfer to the bath. If an arc is maintained while no raw materials are being fed a long, highly radiative arc is set up, and localized bath temperatures increase rapidly. The resulting radiation tends to damage the refractories rather quickly. In a large production furnace, the life of the refractories is crucial to the profitability of the operation. Even relatively short periods (10-15minute) of power input without the feeding of raw materials can have a very marked effect on refractory wear (particularly of the

roof refractories) when the accumulative effect is taken into account over a period of months.

Power Control

The power supply to the 3.2MVA and 200kVA furnaces is phase-controlled by thyristors. This control system can respond very quickly to changing conditions, and precise control of the power input can be readily achieved. Fast control is an attractive feature, but one that is probably not necessary, particularly on larger furnaces where the time constants are relatively long. For this reason, large furnaces use a simpler power supply consisting of a conventional on-load tap changing transformer followed by a diode bridge to produce direct current. The latter system, although slower, is also more robust than the thyristor-based system. Mintek has experienced problems due to failure of the thyristors during overvoltage conditions, and additional schemes to provide protection have had to be incorporated to improve the reliability of the system.

The most important point is that it is necessary to use a power control scheme and not a constant-current scheme, which is more common, since the voltage is affected by the feed and can vary appreciably.

Control of Power and Feed Rate

The feedback and power-control schemes already discussed make it possible to

K.C. Nicol, M.S. Rennie, A.B. Stewart

maintain precise control over these variables, and the problem then shifts to a decision on control of the set point for the power-feed rate ratio. Experience has shown that the most important factor is the control of the total energy fed for a particular mass of raw materials. Minor fluctuations in the balance between the power and the feed rate are not as important provided they are compensated for.

It is possible to calculate the energy required for the reactions based on thermodynamic data and this, together with the steady-state heat loss, forms the basis for the establishment of the power-feed rate set point. However, other factors have to be taken into account. For instance, the precise chemical composition of the raw materials is never known and varies with time, and the heat losses depend on the historical state of the furnace, particularly in regard to any downtime, and also on the current operating state. There is a marked difference in heat losses depending on whether power is being fed with the raw materials or without them.

In practice, the energy requirements for a particular recipe of raw materials are calculated, the steady state heat losses are established, and subtracted from the energy input, and a power-feed rate is set. This set point is then modified on the basis of a combination of feedforward and feedback estimation schemes. Unfortunately, the temperature of the molten bath cannot be monitored

continuously. Non contact temperature measurement techniques (e.g. optical pyrometry) are difficult with an exposed bath, and are ruled out if there is any significant obscuration of the target measurement area. The dense fume and the deposit of cooler material on the surface of the bath are major problems, and non-contact temperature measurement methods do not work within the furnace. Direct contact measurement methods are also ruled out as a result of the high temperature (higher than 1600°C) and the lack of any suitable material capable of lasting for any appreciable time in the environment.

In the absence of any direct temperature measurement, indirect means have to be employed. Temperature and heat-flow measurements on the refractory lining are useful. However, their response times tend to be very slow (more than 2 to 4 hours on the 200kVA facility and much longer on large furnaces) and serve a purpose only in a determination of long-term trends (e.g. lining wear). Water-cooled heat-flow probes installed very close to the hot face have been used with some success, but they suffer from the problem that the heat flowrate to the probe can vary significantly depending on conditions in the bath. Other measurement points are the heat flow to the roof and off-gas ducts, all of which are usually water-cooled. The response time of these measurements can be fairly fast, depending on the extent of refractory cladding on the cooling panels. On the 200kVA facility a

water cooled roof with a carbon-paste lining is used, and the heat flow in the roof responds rapidly to changing conditions in the bath. The other measurement, which is often the only one available on an industrial furnace, is the temperature of the metal or slag monitored during tapping. This is available only during tapping, but does represent a measure of the condition of the molten bath. Unfortunately, the method used for temperature measurement, viz by use of a hand-held optical pyrometer, can give unreliable results, and one requires skill to obtain the measurements and interpret the results.

Because of the problems associated with the estimation of the temperature of the molten bath, it is necessary to continuously monitor the energy balance in the furnace. The calculation is fairly simple and compensates for power-off time by estimation of the fixed and variable heat losses and monitoring of the variables that can be measured. Ideally, a dynamic model, possibly based on feedback-estimation techniques, would be more useful. However, an enormous amount of effort would be required to develop it. Suitable simulation studies have shown that it is necessary to maintain the energy balance because of the large temperature gradients that are developed in an unbalanced situation.

Data Acquisition and Control

The 200kVA and 3.2MVA facilities, being adjacent to each other and powered from the same source, are controlled and monitored by use of the same computer equipment. This consists of a programmable controller (PLC), a dedicated data logger, and more recently, a personal computer (PC) connected to the data logger to provide more flexibility for monitoring and control of the operation. A multipen chart recorder is also available to record long term trends of selected variables.

The major functions of the PLC are: control of the primary variables (feed rate, power, water flows) and the monitoring of any alarm conditions. The data logger performs the standard functions of sampling a number of variables on a repetitive basis, converting them to engineering units, limit checking, and storing averaged information into three variable-time data bases: short averages (minutes), long averages (hours), and shift averages (8 hours). In addition derived variables (e.g. heat flow) can be computed using pre-defined functions. The operator has access to the information via an interactive facility that presents summarizing reports and other information on each variable either on a VDU or a printer. The information is also stored on cassette for subsequent analysis. The data logger has a limited capability owing to its fixed programme design and the personal computer has been

included to provide computational flexibility in the way in which information is manipulated and presented to the operator.

The model referred to previously runs on the PC based on information received from the data logger via a serial communication line.

Results

During the course of a campaign, 96 process averages are stored by the data logger every minute. In addition, the computational ability of the personal computer enables 120 process variables to be stored on the hard disc during every tap (mostly tap-to-tap averages). All this information is subsequently stored on a powerful mini-computer for analysis and the generation of reports. Typical results are shown in Figure 3. These are the tap-to-tap average heat flows from various positions in the side wall of the furnace: at the metal level, just above the slag, and close to the furnace roof. Figure 4 shows the variation in power, total material fed over the tapping cycle and the heat flow measured at the centre plug of the roof based on minute averages over a shift (8 hours). The figure shows when the furnace is tapped (every 2 hours) and how the centre plug responds within the furnace, particularly when material is not being fed.

Conclusions

- (1) The single-electrode d.c. plasma-arc furnace can be used to replace the conventional submerged-arc furnace for the production of ferro-alloys. The major advantages of a plasma furnace are: the ability to process fine material directly, a high degree of flexibility in the choice of raw materials, improved reduction efficiency, and the use of a smaller furnace for the equivalent power level.
- (2) Experience with Mintek's pilot-plant facilities at the 200 to 300kW and 1.2MW levels has shown that consistent stable metallurgical performance can be achieved with a d.c. plasma furnace provided an adequate level of control over the operation is exercised. This level of control is significantly more sophisticated than for a conventional submerged-arc furnace.
- (3) The most important control functions are: accurate control of the feed rate of raw materials, accurate control of the input of electrical power, and the setting of the ratio of the feed of raw materials to the power using a model that takes into account varying conditions in the operation of the furnace.

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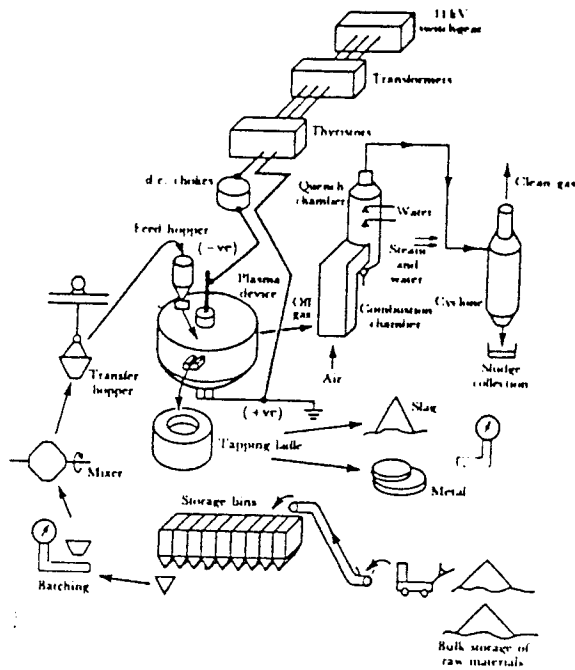


Figure 1. Schematic layout of the 3,2 MVA plasma facility

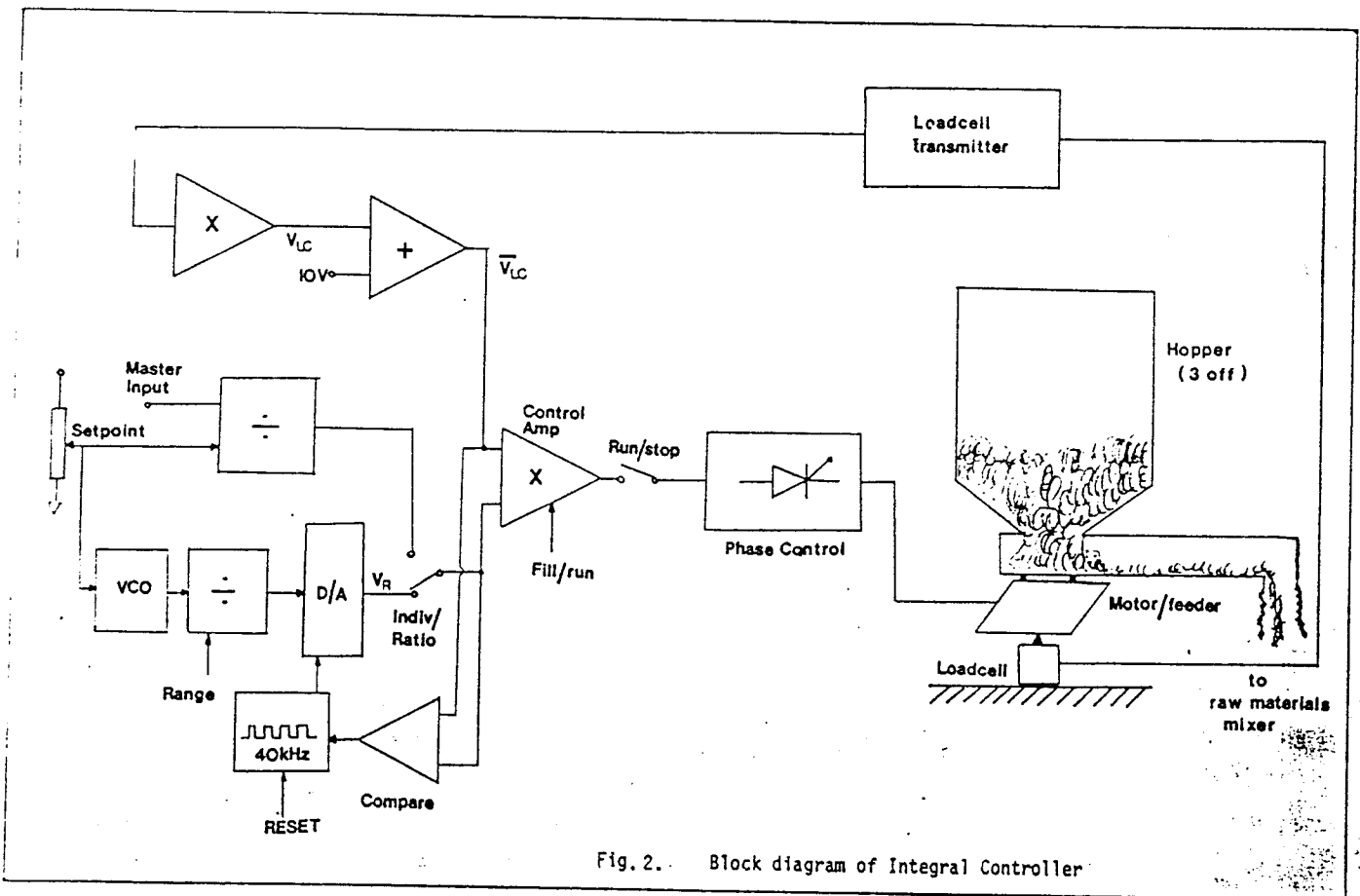


Fig. 2. Block diagram of Integral Controller

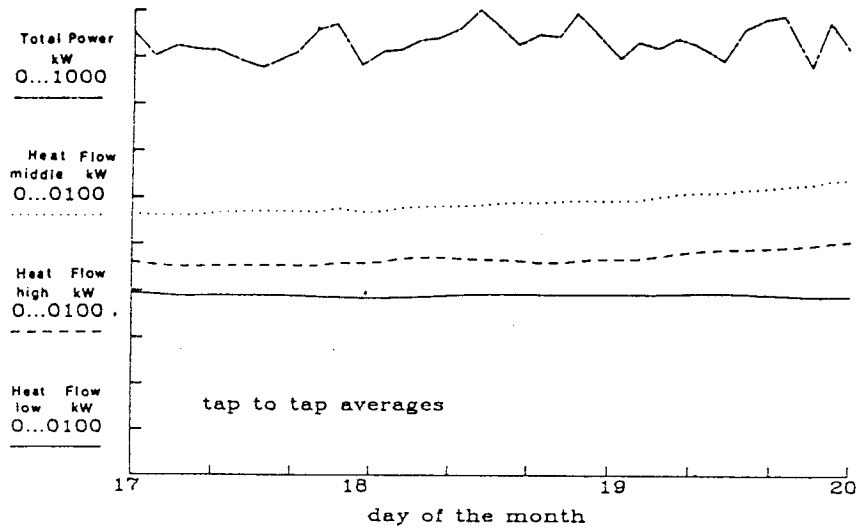


Fig. 3. Power and heat flows over 3 days

