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On-line Laser Measurements of Silica Dust

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At Icelandic Alloys Ltd, the optical density of the silica fume in the stack gas of a ferrosilicon furnace is measured by use of a laser source. This gives an indirect, but instantaneous, measure of the efficiency of the furnace. This system of measurement has proved to be very effective in the evaluation and improvement of stoking techniques, leading to better and more efficient furnace operation.

Introduction

From a metallurgical point of view, the best measure of the performance of a ferrosilicon or silicon-metal furnace is the usage of energy and material per ton of tapped or cast metal. However, tapping and casting are normally batch processes, and therefore all the direct data on furnace performance are bound to be historical by the time that they are ready.

There is, however, a correlation between the furnace performance and its production of silica fume. According to the stoichiometric model of Schei[1] and others, one of the key reactions in the carbothermic reduction of quartzite is the production of SiO(g). Most of the silicon monoxide reacts with carbon in the charge of the furnace in an intermediary reaction before $Si_{(l)}$ is formed. However, some of the silicon monoxide escapes from the furnace, and reacts with oxygen at the furnace top to form silica fumes.

It can be shown (see Addendum) that the specific energy required to produce ferrosilicon, expressed in megawatt-hours per ton of metal, is inversely proportional to the silica recovery in the metal. In a similar manner, it is found that the specific silica fume produced, expressed in kilograms per megawatt-hour, is directly proportional to the silica recovery. These results can be verified with data from the furnaces of Icelandic Alloys (IA). The data are weekly averages from furnace 1 for the period January 1988 to May 1990. The silica recovery is based on the material balance for the furnace and corrected for the accumulation of metal in the furnace as indicated by the material balance. The data are filtered so that all the data for furnace operating times of less than 95 per cent and/or for average running loads of less than 32 MW are omitted from the time series (Figures 1 and 2).

Linear regression shows that the correlation between the specific energy, P_m, and the silica recovery is

$$P_m = \frac{825}{R} - 0{,}625, \qquad [1]$$

with a correlation coefficient of 0,76.

In a similar manner, the correlation between the silica-fume production, P_f, and the silica recovery in the metal is found to be

$$P_f = 201{,}1 - 1{,}934\,R, \qquad [2]$$

with a correlation coefficient of 0,86.

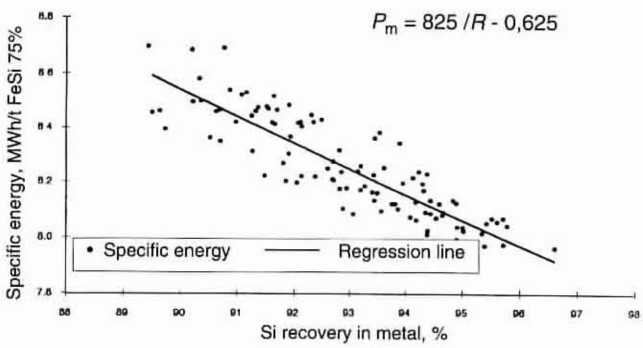

FIGURE 1. Specific energy, P_m, as a function of silica recovery, R

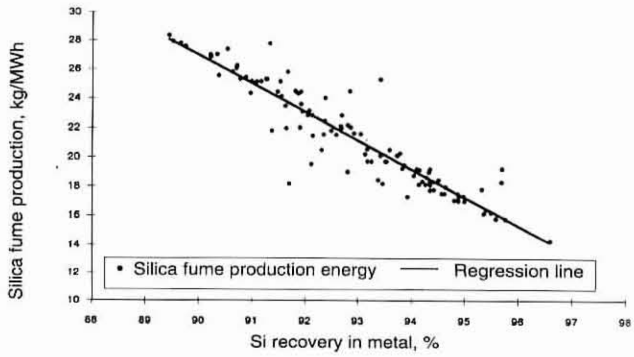

FIGURE 2. Silica-fume production, P_f, as a function of silica recovery, R

Weighing of the Silica Fume

As early as 1981, equipment was installed to weigh the silica fume as it was collected from the baghouse filter and conveyed to compacting and storage silos. The fumes from the filter are conveyed to an intermediary silo. From there, the fume flows to a pneumatic dust-sender unit. The sender unit rests on weighing cells that continuously register the net mass of the sender. At a predetermined mass, the sender is triggered and the dust sent to a compacting and storage silo. The data are sent to the furnace computer, which accumulates the mass of the silica and calculates the silica recovery and other relationships as indicated above.

Figure 3 gives typical results from the weighing of silica. The lower curve represents the raw data, i.e. the accumulated mass of silica. The other curve shows moving averages of kilograms of silica per megawatt-hour with a time constant of 1 hour.

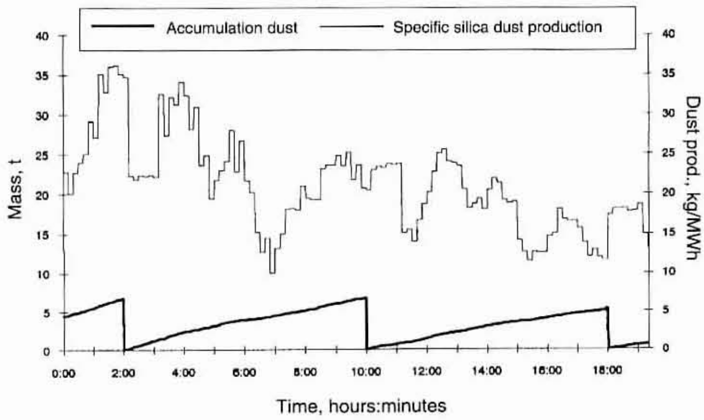

FIGURE 3. Dust production

Since the weighing cells were installed, the data collected have been an integral part of data acquisition for the furnace operation. The cells yield important information on the performance of the furnace, and even on the performance of individual furnace operators, and contribute to a more accurate material balance for the furnaces as described above. The only shortcoming is that the results have a fairly large time constant, owing to both the baghouse filter and the mathematics involved. This means that all the data are smoothed, and thus delayed, before they appear on the computer terminals.

Energy in the Stack Gas from the Furnaces

The next step in the development of a tool for on-line measurement of the silica recovery was to consider the energy in the gas from the furnaces. This method is based on the fact that the reaction between the SiO(g) from the furnace and the oxygen in the air is highly exothermic. For a furnace load of 35 MW and the traditional blend of raw materials at IA, the power in the stack gas can be estimated as a function of silica recovery. This is shown in Figure 4.

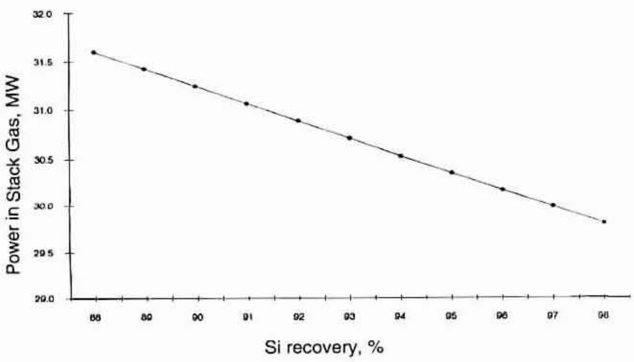

FIGURE 4. Power in the stack gas as a function of silica recovery

Equipment was installed to measure the pressure and temperature drop over the radiclones in the smoke duct of furnace 1. The air velocity in the duct can be calculated from these figures, and the excess energy in the gas is found from the temperature measured in the smoke duct. The results indicate that noise and the inaccuracy of the measurements, and the effects of other variables, make this method difficult or almost impossible to use with the accuracy required.

Optical Measurements of the Silica Fume

In 1989, experiments based on a new approach were started. The idea was to measure the dust concentration in the smoke duct from the furnace, and thus to obtain an indirect measurement of the performance of the furnace.

An optical measuring method was chosen. A laser beam is sent through the smoke duct, through a hole on either side, and the proportion of light that passes through is measured. The dust that is present absorbs and scatters some of the beam; that is, the higher the dust load, the less the light that passes through. The intensity of this light can be used as a measure of the dust load in the duct.

A system based on this method[2] was developed at IA. The system consists of three basic parts: a laser unit that transmits the laser beam, a receiver or sensor, and an amplifier that calculates the real dust concentration from the measured values.

The laser unit consists of a laser diode (the laser source) that is mounted on a laser pointer. This pointer secures the exact adjustment of the laser diode, allowing rotation and translation about two axes. The laser unit is enclosed in a weather-proof box that is mounted directly on the duct (Figure 5).

The main part of the receiver is a photodiode with a collimator. The receiver, along with the amplifier, is enclosed in a box on the duct opposite the laser. The units are connected via a signal cable each to a connection box. This connection box requires a power supply of 220 V a.c., and has an analogue output of 4 to 20 mA.

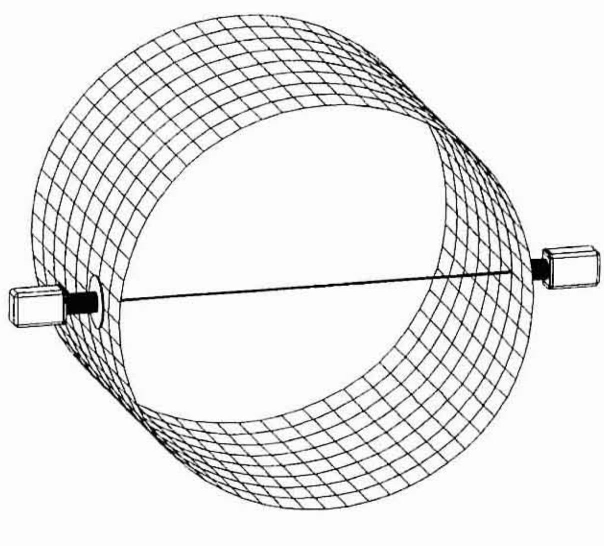
FIGURE 5. The laser dust monitor

Installation

Before the system was installed, several factors had to be considered. For example, the location of the measuring equipment had to be chosen carefully, since the duct had to be as straight as possible to avoid turbulence in the air stream. At IA the best location was found to be on the roof of the furnace building. At this location, the gas is pulled towards the cooler by fans, resulting in under-pressure inside the duct. Because of this under-pressure, air flows into the duct through the holes on either side of it. This effect makes ventilation of the equipment unnecessary. To ensure that no dust can accumulate on the laser unit and the receiver even if the pressure inside the duct should occasionally change, the equipment is positioned 19 cm from the duct.

Figure 5 shows how the equipment is attached directly to the duct without any extra platforms. Thus, the equipment follows the movements of the duct resulting from the changing temperature inside it.

Signal Processing

The output current from the sensor is related to the dust density by equation [3]:

$$\frac{I_o}{I_i} = 10^{-D}, \text{ where} \qquad [3]$$

I_o is the measured current

I_i is the measured current with a clear duct (no dust), and

D is the extinction.

$$D = k \cdot l \cdot m, \text{ where} \qquad [4]$$

m is the concentration of dust in the duct

k is the extinction coefficient, which depends on factors such as the particle size of the dust

l is the path length of the laser beam in the smoke duct.

The measured signal is fed to an amplifier, which calculates the extinction according to equation [5]:

$$D = -\log_{10}\left(\frac{I_o}{I_i}\right). \qquad [5]$$

The value of D is then sampled and fed to a computer, where it can be processed further and displayed graphically on a screen.

The value of k can be estimated theoretically but, for more exact quantitative measurements, a calibration is needed. If k is known, the dust concentration can be calculated from the extinction by

$$m = \frac{D}{k \cdot l}. \qquad [6]$$

To calculate the exact rate of dust production, W, in grams per second, the velocity, v, of the gas stream in the duct is needed:

$$W = m \cdot v. \qquad [7]$$

Division by the energy, P, yields the more familiar quantity, G, which is the production of microsilica per unit energy:

$$G = \frac{W}{P}\left(\frac{\text{kg}}{\text{MWh}}\right). \qquad [8]$$

Various methods are currently in use to measure the gas velocity, but most of them are relatively complicated and inexact. A simple method that should give good results is now being developed. It consists basically of two similar laser systems, separated by the distance L in line with the gas flow on the same duct. Based on the signals from both sensors, it should then be possible to calculate the time, t, that it takes the dust load to travel distance L. Then, the velocity would be calculated from

$$v = \frac{L}{t}. \qquad [9]$$

This method has not yet been fully tested. However, if it is successful, the system described in this paper will be directly applicable for this purpose. The only addition needed would be a second laser system and the appropriate computer software.

If k cannot be determined accurately enough, or if v is not known, some valuable quantitative information can, nevertheless, be drawn from the extinction itself, regarding the *relative* changes in the dust load.

Modulation of the Laser Beam

An optical filter that filters out light at wavelengths different from that of the laser (670 nm) is placed in front of the sensoring photodiode. Ambient light, mainly from sparks in the smoke, with wavelengths near to 670 nm may, however, reach the diode and can disturb the measurements.

To overcome this problem the laser beam is modulated. The amplifier is then able to filter out the signal that corresponds to the laser beam and to use only this in its calculations.

Correlation with the Dust Mass

The mass signal mentioned earlier gives very valuable information to the furnace operator. However, it is delayed, with a time constant of approximately 1 hour, and can therefore not be used for an instant evaluation of the need for stoking as is the case for the laser signal. Nevertheless, the mass of the dust produced can be used as a reference in estimating the accuracy of the laser system.

Figures 6 and 7 show the laser signal and this mass signal, both filtered with a time constant of 66 minutes and 11 hours respectively. Figure 6 shows particularly well the delay from the laser to the mass signal. This comparison gives some idea of the great accuracy of the laser signal. This has also been verified numerically.

This correlation can also be used to calibrate the laser signal, as described earlier.

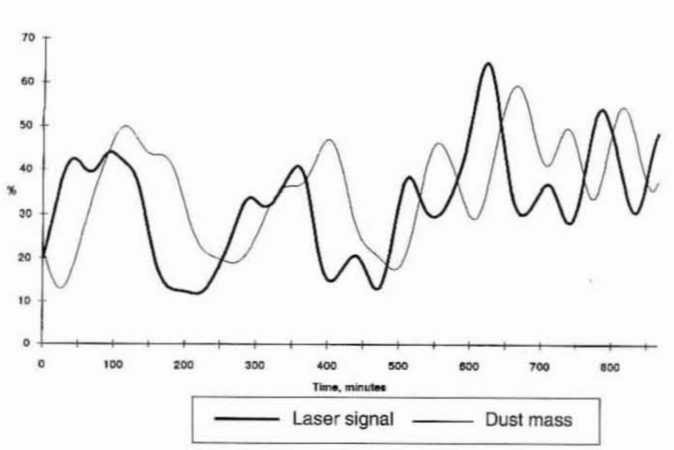

FIGURE 6. Laser signal compared with the dust mass (filter constant = 66 minutes)

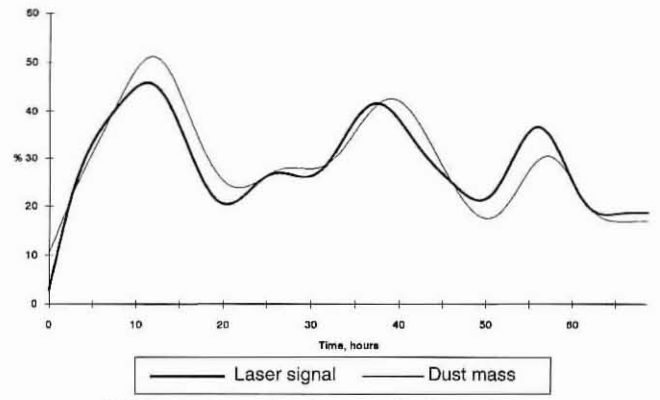

FIGURE 7. Laser signal compared with the dust mass (filter constant = 11 hours)

Evaluation of Stoking Techniques

At IA, the processed signal from the amplifier is displayed on a computer screen, together with a signal showing when the stoking car is in operation. The effects of stoking and charging can clearly be seen in Figure 8. This practice has proved to be very valuable for improving the furnace operation. A considerable difference has been found in the quantities and patterns of silica-fume production by different furnace operators or different shifts.

Stoking techniques were studied[3] with reference to patterns of segregation in the mix of raw materials in the furnaces, and to current ideas of the chemistry of the production. From these studies, improved stoking procedures were devised, leading to a substantially better recovery of silicon. The operators at IA find the laser dust monitor indispensable for proper maintenance of these procedures, and for minute-to-minute information on the efficiency of the furnaces.

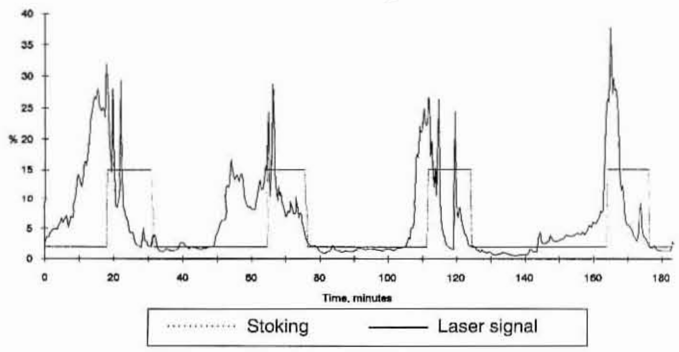

FIGURE 8. Measurements of dust concentration in the smoke duct

Addendum: Specific Energy and Silica Recovery

The correlation between the production of silica fume, the recovery of silicon in the produced metal, and the energy required for the process is shown by the following simplified model of the total reaction:

$$SiO_2 + (1+\mu)\,C \rightarrow \mu\,Si + (1-\mu)\,SiO + (1+\mu)\,CO, \qquad \text{[A1]}$$

where μ is a constant, $0 < \mu < 1$, that indicates the proportion of silicon in the quartzite recovered in the metal. The percentage silicon recovery, R, is defined as 100 μ. Equation [A1] can be separated into the following equations:

$$SiO_2 + 2\,C \rightarrow Si + 2\,CO\,; \qquad \triangle H_f(1) \qquad \text{[A2]}$$

$$(1-\mu)\,Si + (1-\mu)\,CO \rightarrow (1-\mu)\,SiO + (1-\mu)\,C\,; \quad \triangle H_f(2), \qquad \text{[A3]}$$

where $\triangle H_f(1)$ and $\triangle H_f(2)$ are the molar heats of the reactions with reference to silicon.

The total energy required for the chemical reactions shown in equation [A1] is thus

$$\begin{aligned} \triangle H_{total} &= \triangle H_f(1) + \triangle H_f(2) - \mu\,\triangle H_f(2) \qquad \text{[A4]} \\ &= \triangle H_f(1) + \triangle H_f(2)\,/\,\mu\,\triangle H_f(2) \\ &= a\text{-}\mu b, \end{aligned}$$

where a and b are constants.

If it is assumed that all the other energy-related variables, such as furnace load, energy required for the reduction of impurities, heat losses due to cooling and radiation, latent heat of the molten metal, etc., are constant, the specific energy required to produce ferrosilicon is, with reference to equations [A1] and [A2],

$$\begin{aligned} P_m &= K \cdot \frac{a-\mu b}{\mu} \qquad \text{[A5]} \\ &= \frac{A}{\mu} - B \text{ (MWh)} \\ &= \frac{A'}{R} - B' \text{ (MWh/t)}, \end{aligned}$$

where K, A, and B are constants. This means that the specific energy is inversely proportional to the silica yield in the metal.

In the same manner, the correlation between the energy and the silica fume produced, expressed as kilograms of silica per megawatt-hour, is

$$\begin{aligned} P_f &= K' \frac{1-\mu}{a-\mu b} \qquad \text{[A6]} \\ &= \frac{100-R}{100C-RD}, \end{aligned}$$

where C and D are constants, and R is the silica recovery. If $P_f > 0$, then $C > D$. Hence, P_f is proportional to R as R approaches 100.

References

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