Environmental Aspects of Ferro-Silicon Furnace Operations-An Investigation of Waste Gas Dynamics

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Abstract

The Norwegian FerroAlloy Association (FFF) has been promoting research work in order to understand and to improve the silicon and ferrosilicon process. One of the projects has dealt with the waste gas dynamics. The objective of this project has been to achieve a better understanding of the process as well as the environmental aspects. The project includes comprehensive measurements at a 42 MW ferrosilicon furnace as well as theoretical studies and modelling work. The main gas pollutants NOx, CO2 and SO2 has been examined. Also crater pressure dynamics and charge temperatures has been measured. Large variations in waste gas composition as well as off-gas temperature during the normal furnace operations such as stoking and charging has been found. The knowledge from this project will be used in order to meet new and stricter environmental regulations as well as to improve the furnace operations.

Introduction

In previous studies we have analysed the mechanisms controlling clogging of off-gas channels from FeSi furnaces [1]. During this work it was revealed that the gas composition and temperature varies strongly with time. The operation cycle on the actual test furnace turned out to have significant effect on the local temperature distribution as well as the chemical composition of the gas. By analyses of the flow pattern, CO combustion and turbulent deposition rates of particles we were able to reduce clogging and allow more even and on an average bases higher off gas temperatures. Hence, we were able to increase the recovery rates of electric energy from the waste gases.

The observed dynamic behaviour of the off-gas composition indicates that a more fundamental understanding of the process is called for. If the environmental performance of the process is to be improved such a fundamental understanding is crucial.

The Norwegian FerroAlloy Associations (FFF) has taken this challenge, and has been promoting research work in order to understand and to improve the silicon and ferrosilicon process. Hence, a new project for launched for detailed investigation of the waste gas dynamics. The objective of this project has been to achieve a better understanding of the process as well as the environmental aspects. In this paper we present results from comprehensive measurements at a 42 MW ferrosilicon furnace and give some guidelines for how to improve the environmental performance.

Full scale experiments

Full scale experiments were conducted in a two-day campaign in June1996 at Furnace 2 at the Elkem plant at Thamshavn, Orkanger. The furnace with off gas system and boiler is schematically shown in figure 1. In the figure we see the locations of the experimental stations.

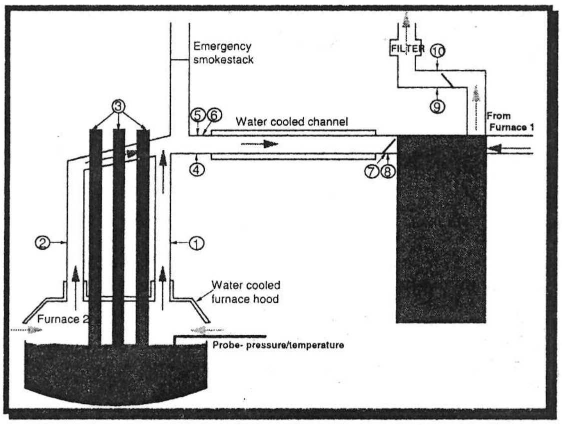

Figure 1 The experimental stations at Furnace 2 (42 MW) at the Elkem plant at Thamshavn, Orkanger, Norway.

In the positions 1,2,4 and 8 fast thermocouples measured the off-gas temperature. Note that the temperatures in the two riser channels from the furnace may be very different. At position 3 we measured the individual pressures in the craters at the bottom of the electrodes. This was done by feeding 6.3 mm id steel tubes into the electrodes [2] until contact with the crater zones was obtained. Then the crater pressures could be monitored directly via the gas column in the tubes.

In position 5 samples of the dust (silica and soot) were taken by a thermophoretic sampler [3]. These samples were taken every 10 minutes and analysed for surface luminance by an optical technique. In position 6 the gas composition (CO, CO_2, O_2, SO_2 and NO_x) was analysed.

The silica dust concentration was monitored in position 9 by a laser. Close to this position (8) the gas flow rate was reported by an S-tube (Pitot principle).

Finally a special probe was designed to measure in-charge temperatures and pressures.

In the probe both pressure and temperature was reported from two different positions.

In addition to this the opening of the furnace doors, valve opening due to charging of raw materials and the movement of the stoking truck was monitored electronically.
The data was logged digitally every 5 seconds from all measuring stations. In addition standard process data was logged at the plant and was made available to the research team.

Experimental results

Temperature fluctuations

In figure 2 we see the measured temperatures at position 4 (figure 1). During the first day raw materials were fed semi-continuously into the furnace while on the second day the feeding was performed batch wise ever 30 minutes. In figure 2 we see significant temperature fluctuations both days. The general temperature increase the first day is due to a deliberate reduction in suction of air into the off-gas system.

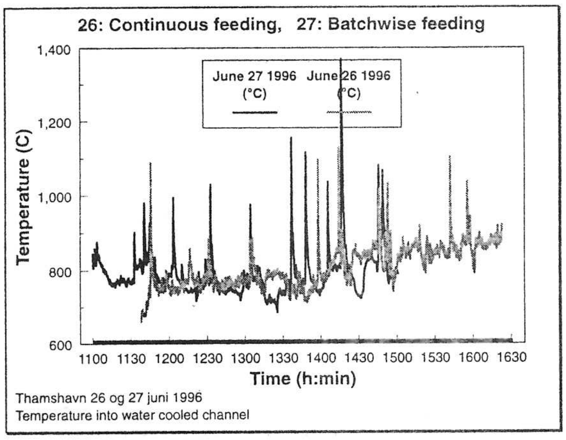

Figure 2 Experimental temperature from position 4, figure 1.

The observed temperature fluctuations were found to be rather independent of the operations on the furnace. In figure 3 we see that the off-gas temperature show peaks in periods of stoking/feeding and also occur in periods when the furnace hoods are closed and there is no operator-imposed activity on the furnace.

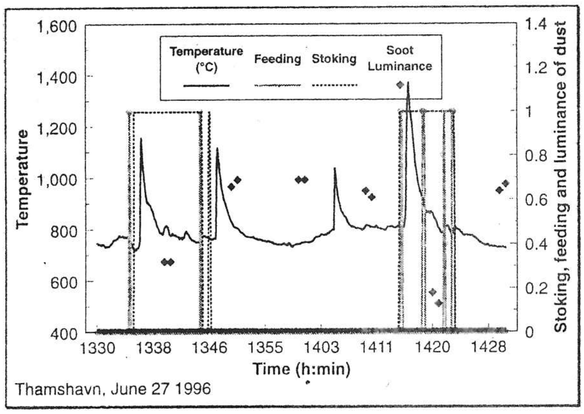

Figure 3 The figure display temperature (position 4) and periods for feeding and stoking. The symbols denote measured luminance (0.0-1.0) of the dust sampled by the thermophoretic probe.

It is evident that these temperature bursts is due to processes taking place inside the furnace in the charge materials, possibly in the crater region at the bottom of the electrodes.

Soot production

From figure 3 we see that the luminance of the dust (soot and silica) is low during furnace maintenance. During normal operation the dust is brighter (high luminance). This is mainly due to the dilution of soot by silica in periods with high silica production. However, we have got some indications that the soot production may be higher in periods with stoking and feeding.

Off-gas composition

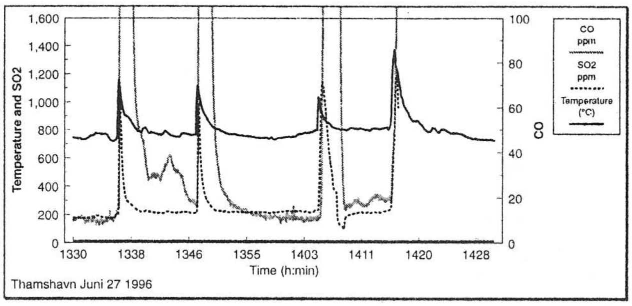

Figure 4 Temperature (position 4) and gas composition (SO_2, CO).

The off gas composition was found to vary in close agreement to the large scale temperature fluctuations. The temperature bursts as seen in figure 2 was usually accompanied with high concentrations of SO_2, CO_2, CO and some times high SiO_2 concentrations. Simultaneously, the oxygen level dropped as expected. This can be seen from figure 5. The SO_2 concentrations had usually a level of 400 ppm. However, at the second day when the consequences of the more batch-wise feeding became apparent the average SO_2 level seemed to drop below 400 ppm as seen in figure 4. This was followed by much larger fluctuations in the gas composition and here SO_2 arrived at some extreme peak values. In the experiments we could not conclude if the reduced SO_2 release was permanent or temporary. In case a temporary reduction can be proved the sulphur has to transported out as a non gaseous component.

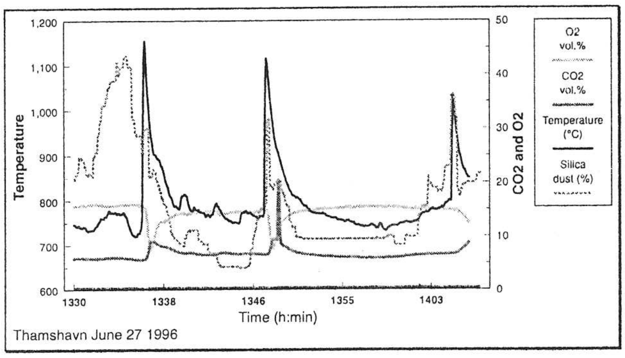

Figure 5 Temperature, silica dust and gas composition (CO_2, O_2).

The large fluctuations in gas composition seen in figure 4 may be related to inhomogenious composition and temperature of the charge. This will be discussed more below.

NO_x emissions

It was expected that we might see some correspondence between temperature and NO_x emissions. In figure 6 we see that the temperatures in position 4 (figure 1) peak while there is no response on the measured NO_x concentration. However, we see a clear correspondence between dust concentration (mainly silica) and NO_x emissions.
This is more clearly shown in figure 7 where the experimental NO_x concentrations are plotted against temperature and dust (silica) concentration. We find a clear relation between dust concentration and NO_x emissions. Off gas temperatures seems to have no impact on the NO_x emissions. The only explanation for this phenomenon must be that the flame zones during SiO combustion is very hot and that thermal NO_x is formed and released. The production rate of NO_x is therefore expected to be proportional to the volume of the SiO flame.

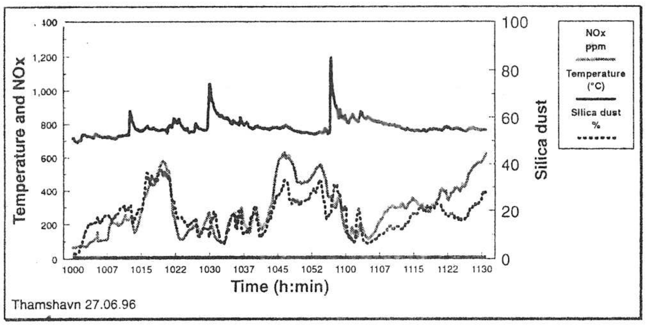

Figure 6 Experimental temperature in position 4, silica dust concentration and NO_x concentration.

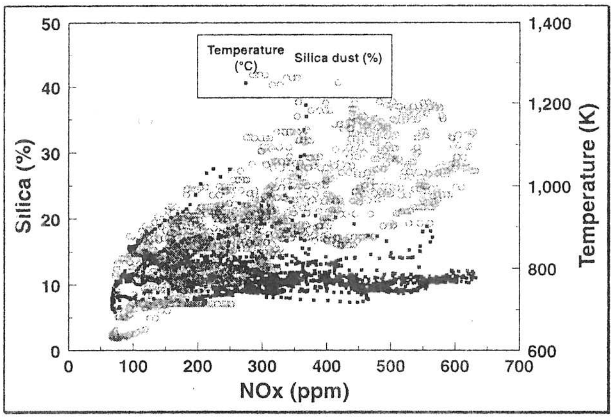

Figure 7 Measured NO_x-concentration plotted against silica concentration and gas temperature.

Charge temperature

Temperatures reported by the charge-probe are shown in figure 8. We find that the temperatures just below the charge surface were close to 1300 °C. These high temperatures was quite unexpected and indicates that chemical reactions may take place all the way up to the charge surface.

At 13:20 hours the charge probe is covered by approximately 1 m^3 of cold charge mass. The temperature at the lower and hottest thermocouple is clearly more stable even if the temperature level is unchanged. At the upper thermocouple the temperature drops as the thermocouple is submerged in cold charge mass. It is seen that the temperature increase very slowly in the fresh charge volume, approximately 200 °C each hour. This give strong support to a hypothesis that there exist pockets of charge material which is relative cold. It is possible that volatile components in carbon materials may exist for longer times in such regions. Hence, soot formation may depend on this phenomenon.
It is interesting to note that fresh, cold charge on the surface of the furnace bed stabilise the observed temperature fluctuations. One explanation for this may be that at the bottom of the fresh charge a layer of very low permeability material is formed, mainly due to percolation of fines through the coarser charge. Hence, the local velocities in the charge are reduced and the temperatures become more controlled by radiation and conduction than by convection.

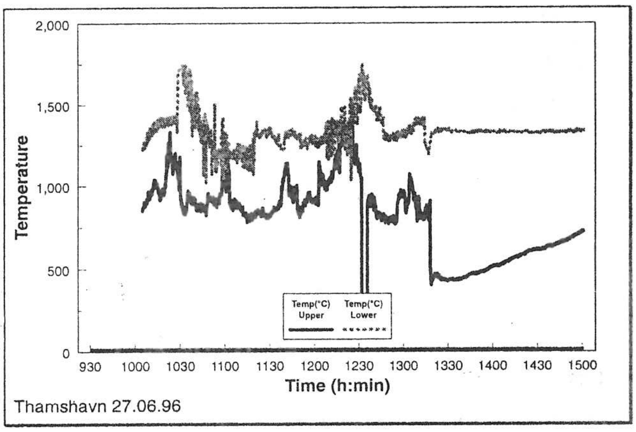

Figure 8 Temperature measured by the charge probe. The upper thermocouple is just outside the charge surface (until 13:15 hours) while the lower is always inside the charge.

Electrode (crater) pressures

The steel tubes fed through the electrodes reported crater pressures in periods. Partially the tubes were blocked, probably by SiO gas from the crater which might condense inside the relatively colder tubes. In the periods when electrode pressures were reported information like seen in figure 9 was obtained. We see that when the electrode (crater) pressure (only electrode 3 here) is low the silica dust production is high. This shows that the charge is relative open and SiO gas is allowed to escape and combust to SiO_2. In other periods the electrode pressure is high and SiO release is almost insignificant. It should be noted that this picture is somewhat incomplete as we for this period had only good measurements for one of the electrodes. However, the electrode pressures seem to be only partially connected. This indicates that the cavities formed close to the three electrode tips may only part time interconnect.
A further interesting result is that the electrode pressures may be as high as 0.1 atmosphere over ambient pressure. This indicates that the permeability of the charge may be extremely low in periods.

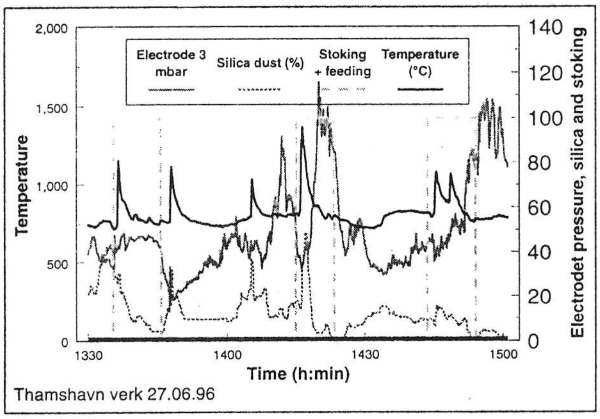

Figure 9 Observed off gas temperatures, electrode pressures, silica dust concentration and periods for stoking/feeding.

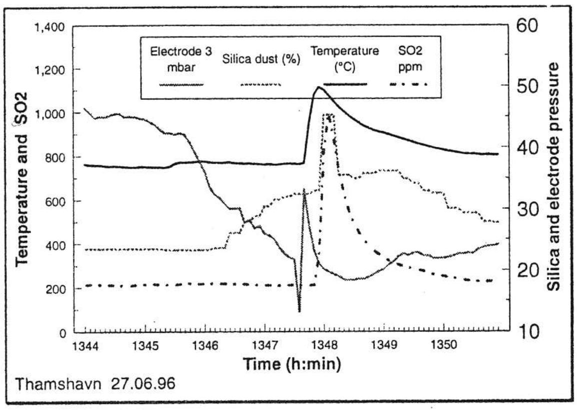

Figure 10 The figure shows a detail from figure 9.

If we plot the results from figure 9 close to hours 13:48 with a higher time resolution we see the result in figure 10. The electrode pressure drops slowly and the silica production increase at a relatively constant rate. At time 13:47:40 the pressure drops first abruptly, then increase rapid, relax and finally increase slowly. We interpret this as an avalanche in the charge mass close to the electrode. The avalanche opens up the top of the charge temporarily (first minimum), then the mass is falling or sliding and thereby transmits drag force to the gas. This causes the pressure peak followed by a relaxation to a more stationary situation. The interesting phenomena here is that the avalanche seems to trig an outburst of SiO_2, SO_2 - and CO_2-gas. At this time the furnace is not disturbed by the operators or by feeding.

Analyses of the experimental data

One of the most pronounced features seen in the present study is the outburst of SiO_2, SO_2 - and CO_2-gas accompanied by high gas temperature. If we assume that there is no leakage of false air into the off gas system the energy in the temperature bursts correspond to CO volumes ranging from 250 to 1000 m^3 or SiO volumes approximately ranging from 50 to 200 m^3. Such large volumes of combustible gases cannot be hidden in porous volumes inside the charge in the furnace. The only explanation so far for this peculiar behaviour is that devolatilization and carburization of coal in the charge has been incomplete. When charge mass containing volatiles are sliding into the extremely hot crates zone the volatiles are released. Such a behaviour is not likely believable. However, several of the results support such a hypotheses.

i) If charge is loaded in large heaps the charge mass heats up very slowly. This can be explained by fines in the charge which percolate to the bottom of the heap and create a layer of very low permeability. Hence, convection of hot furnace gas will contribute only very little to the heating of the new charge material.
ii) The high temperature bursts seem to be trigged by avalanches in the charge.
iii) After changing the charging pattern the average release of SO_2 gas is reduced though the peak values seem to increase. This may indicate that the more batch-wise feeding lead to a more inhomogenious charge.
iv) The pressure in the electrode craters may be as large as 0.1 atmosphere above ambient pressure. One possible explanation for these high pressures is that SiO-gas condense on the colder charge, and in some regions form pockets of relative charge which are wrapped in condensed SiO. In such a case the permeability of the charge may be very low.

The point of charge permeability was examined by simulations of the flow pattern through the charge. We used an in house modified version of the commercial CFD-code FLUENT V2.98 [4]. The computed pressure drops through the charge was low compared to the experimental values. By assuming 25 mm diameter raw material particles and a gas volume fraction in the charge of 0.1 the crater pressure was computed to be 360 Pa which is approximately a factor 30 lower than the experimental peak values. On the other hand the hydrostatic head of one meter charge is 10 000 Pa if we take the bulk density to be 1000 kg/m^3. This tells that if the charge becomes completely impermeable 1 meter down from the surface the experimental peak pressures may be explained. In such a case the gas pressure inside the charge build up until "the lid" breaks and as a consequence initiates an avalanche which again trigs the outburst of combustible gases.

Conclusions

The NO_x release from a ferrosilicon furnace is highly correlated with silica dust production. By good furnace operation, having a large yield of silicon, the NO_x emissions may be kept low. Furthermore, the NO_x-emissions are not found to depend on the average off-gas temperature. Hence, a high heat recovery of the off-gas energy can be obtained without a risk for increased NO_x-emissions.
The experimental data have given strong indications that internal avalanches in the charge seem to have a crucial effect on the off gas temperature and composition. The avalanches seem to happen at quite regular intervals and are to a large extent independent of furnace operations like stoking.
The charge avalanches may be caused by high crater pressures due to low permeability in the charge, possibly caused by SiO condensation.
The avalanches cause outbursts of large quantities of combustible gases which may come from pockets of poorly carbonised charge material. The possibility of inhomogenities in the charge materials was verified by experiments which showed that in a large (approximately 1 m^3) pile of raw materials the temperature increased only by 200 $°C$ per hour.

The soot contents in the silica dust is largest during stoking. When silica production is high the soot mass fraction of total dust is lower.
More work is needed to understand the mechanisms which control the soot formation and soot combustion in the off gas.

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