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HOLLOW ELECTRODES IN THE PRODUCTION OF FESI75

H. T. Ingason* J.Halfdanarson* J.A.Bakken**

* Icelandic Alloys Ltd., Grundartangi, Iceland
** Norwegian Institute of Technology, Division of Metallurgy

ABSTRACT

Full scale industrial experiments have shown that FeSi fines can be remelted in an economic way by the use of a hollow electrode. A moderate charging through the electrode does not affect the daily operation of a FeSi (75%) furnace in any negative way. The injection of nitrogen through a hollow electrode leads to an increase in the arc resistance while the charging of FeSi75 fines has a very small influence. The experience so far indicates that feeding of quartzite fines tend to clog the centre hole. The hole increases the operation safety of the Söderberg electrode by decreasing the risk of electrode hard breakages.

INTRODUCTION

One of the two FeSi75 production furnaces at Icelandic Alloys plant at Grundartangi has been equipped with a centre hole in one of the three electrodes. Particles and gas are charged through the hole, directly to the gas filled crater at the tip of the electrode. The research project was launched in 1991 and has been jointly financed by Icelandic Alloys Ltd., ELKEM a/s and the Nordic Industrial Fund. It is based on a number of full-scale industrial experiments. Numerical modelling has also been a vital part of the project. New numerical models have been developed for the purpose of the project, in addition to the existing models that have been utilised.

The experiments consist of the following phases:

- Continuous operation and control of the centre pipe
- Measurements of the temperature profile in the electrode
- Feeding of FeSi75 fines
- Feeding of quartzite fines
- Feeding of carbon powder.

The project has been a basis for a dr.ing. (Ph.D.) study at the Norwegian Institute of Technology. This paper discusses the project and some of its results. The details can be found in [1].

EXPERIMENTAL

The hollow electrode is a modified *Söderberg electrode*. The centre hole for charging gas and particles is 10 cm in diameter. It is made of steel pipes that are placed in the centre of the electrode, and secured radially with steel rods. New steel pipes are added on at the top when new electrode casings are welded on.

The equipment for the experiments consists of the following main-parts:

- A production unit for nitrogen
- A silo that can contain up to 4 m^3 of material,
- Conveyor 1 - with a fixed rotational speed
- Conveyor 2 - with a controllable rotational speed
- A control box

The nitrogen is fed into an almost air tight charging system. The material to be charged through the electrode is transported in smaller transporting silos from the ground floor to the main material silo on the fourth floor. The flow rate of material can be adjusted both by changing the rotational speed of the lower screw conveyor, and by changing the start- and stop periods of the conveyors. Fig. 1 is a schematic overview of the charging system.

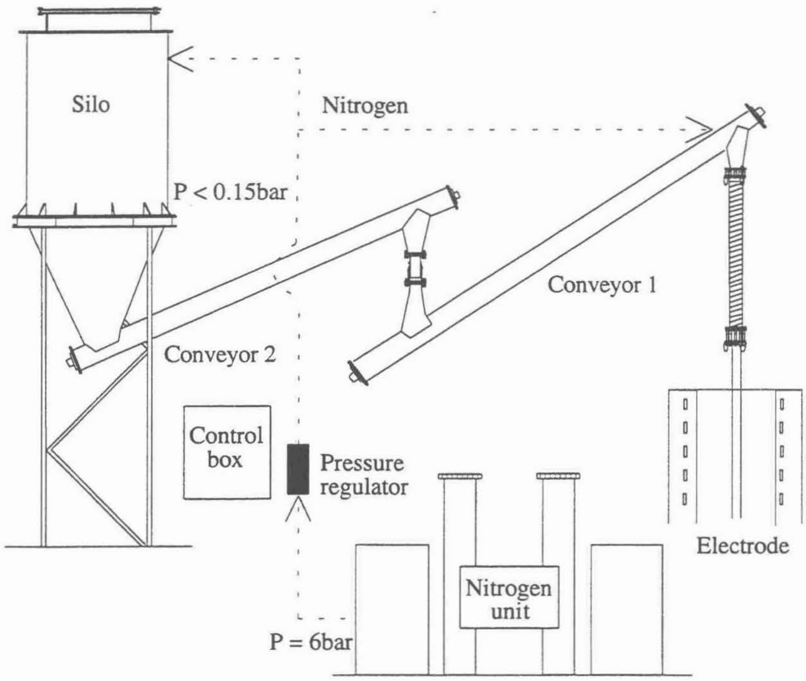

FIG. 1. A schematic overview of the charging system.

REMELTING OF FESI75 FINES

FeSi75 fines are formed when cast metal blocks are crushed. The formation of fines is undesired as the market price for fines is lower than for the standard material. Some of the FeSi75 fines are remelted in the casting moulds. The fines are also sold when the market price is high enough. The aim of the experiments with the hollow electrode is to explore a new method of remelting FeSi75 fines by feeding them directly to the furnace through the electrode.

Analysis of data from long-time measurements

The quantity of remelted FeSi75 fines is approximately 6 tons/day or roughly 6% of the daily production of FeSi75 (18% of the production of one crater). In order to detect the effect of charging FeSi75 fines on some of the operational variables of the furnace, 24 hour average or accumulated values of these variables are analysed specifically. The data consists of 164 data points. A total of 4 variables is analysed, along with the daily charging rate of FeSi75 in tons (Ch). These variables are: Total energy consumption of the furnace in MWh (En), the quantity of quartzite charged to the furnace in tons (Qu), the net tapped metal from the furnace in tons (Ta) and the dust production in tons (Du). The analysis is made by the use of linear regression. The following three models are constructed:

$$Ta = k_1 Qu + k_2 Ch + a \quad ; \quad Du = k_3 Qu + k_4 Ch + b \quad ; \quad Qu = k_5 En + k_6 Ch + c \qquad (1)$$

TABLE 1. Calculated regression coefficients.

	k_1	k_2	a	k_3	k_4	b	k_5	k_6	c
Value	0.531	0.996	0.969	0.099	-0.079	4.917	0.201	-0.160	8.583
Stdev.	0.030	0.256	4.895	0.014	0.124	2.372	0.005	0.214	4.072
Significance	100%	100%		100%	48%		100%	54%	

The calculated coefficients are listed in Table 1 which also shows the standard deviations of all the parameters. The last row lists the significance level of the parameters. The number represents the significance level at which the null hypothesis can be rejected, i.e. the hypothesis that an independent variable *does not* affect the dependent variable.

Fig. 2i is a scatter diagram of tapped FeSi75 (Ta) versus charged FeSi75 fines (Ch). The figure shows that Ta increases with increased Ch. The correlation coefficient between Ta and Ch is shown in the figure The correlation coefficient is r=0.28 and it is significant at the 100% level. The change in tapping (Ta) caused by a change in charging (Ch) at a fixed quartzite input (Qu) can by expressed by:

$$\left.\frac{\partial Ta}{\partial Ch}\right|_{Qu} = k_2 \qquad (2)$$

The value of the coefficient is k_2 = 0.996 (Table 1) and the coefficient is significant at the 100% level.

Fig. 2 ii is a scatter diagram of dust production (Du) vs. charged FeSi fines (Ch). The correlation coefficient between Du and Ch is r=0.02 and is not significant.

Fig. 2 iii is a scatter diagram of energy consumption (En) vs. charged FeSi fines (Ch). There is no obvious correlation between these variables according to the figure. The change in energy consumption resulted by a change in charging rate, at a fixed quartzite input can by calculated as follows:

$$\left.\frac{\partial En}{\partial Ch}\right|_{Kv} = -\frac{k_6}{k_5} = k_7 \qquad (3)$$

The value of k_7 is 796 kWh/tn FeSi75 which is remarkably close to the theoretical energy required to heat and melt FeSi75. The coefficient k_6 is, however, only significant at the 54% level. The coefficient k_7 is therefore *not significant*.

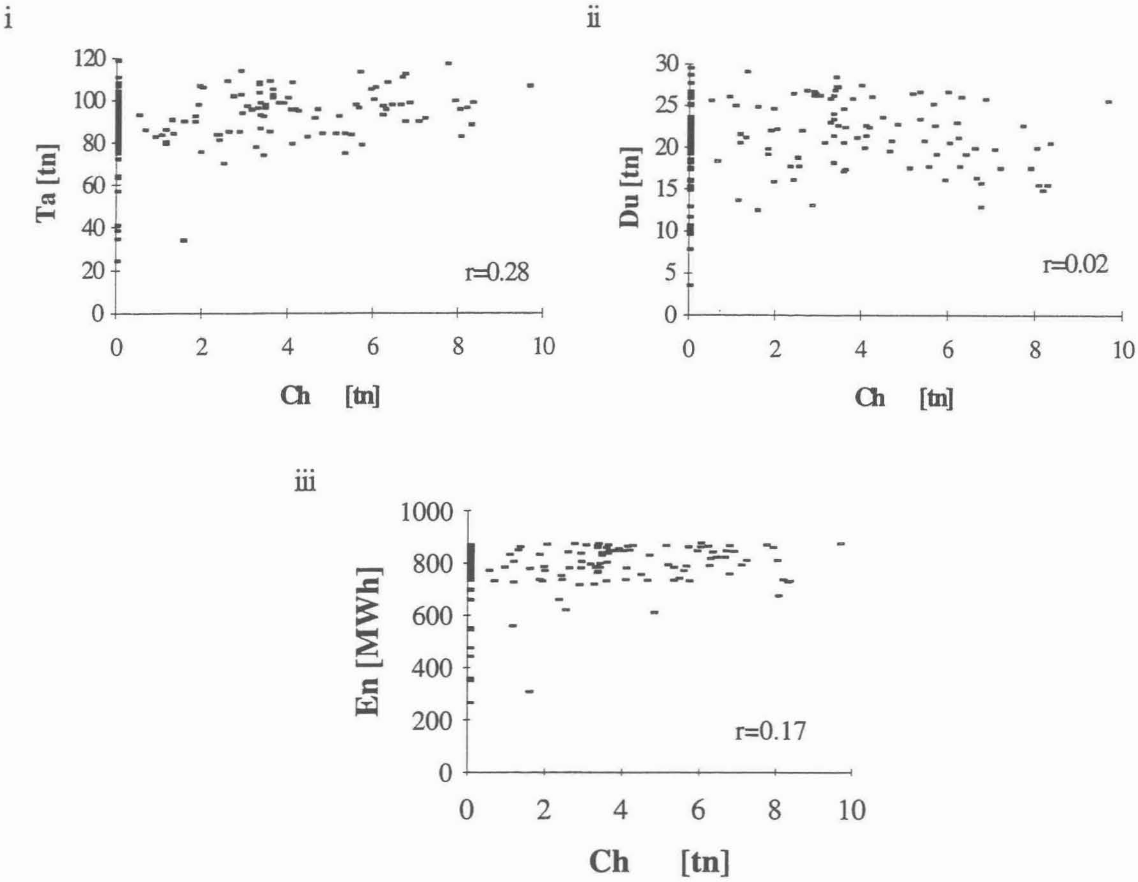

FIG. 2. i. Scatter diagram of Ta vs. Ch, ii.scatter diagram of Du vs. Ch, iii. scatter diagram of En vs. Ch.

<u>Effectivity of remelting</u>

Barium rich FeSi75 has been fed through the hollow electrode. This material is of similar chemical composition as the FeSi75 produced at Grundartangi, but with a barium content of 1%. The experiment was made in order to observe how soon the charged material fines are tapped out of the furnace. Tapping samples were collected before, during and after the experiment, as well as samples of the produced dust. The samples were analysed in order to detect any changes in the barium content as a result of the experiment. No increase of Barium was detected in the dust. Fig. 3 shows the content (%) of Al, Ca and Ba in *tapped metal* before, during and after the charging. The tapping hole was close to the hollow electrode. The notation N, D and E on the x-axis denotes the three shifts, night shift (N), day shift (D) and evening shift (E). The numbers correspond to the number of tappings during each shift. The figure shows that there is a peak in the barium content five tappings after charging starts. This implies that the FeSi75 fines are collected as tapped metal shortly after they are charged through the hollow electrode.

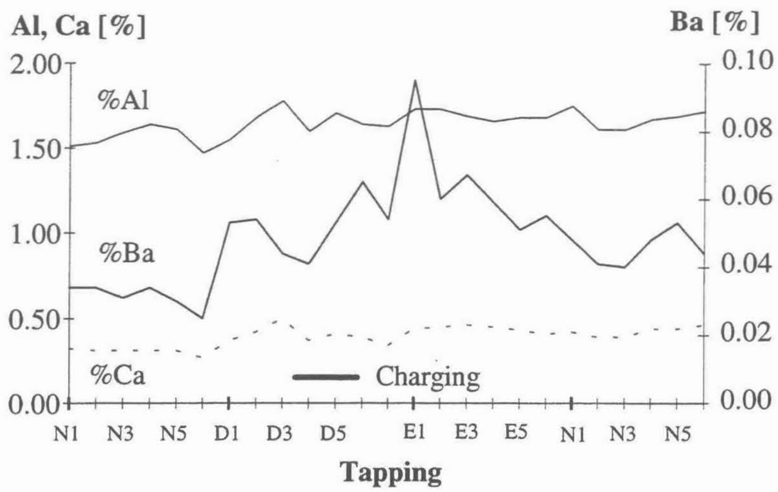

FIG. 3. Al, Ca and Ba content in tapped metal.

Conclusion

The charging of FeSi75 fines in a stream of nitrogen through a hollow electrode in a FeSi 75 furnace is an efficient method of remelting FeSi75 fines. There is no indication that this remelting of FeSi75 fines affects the furnace operation in a negative way. It is concluded that practically all the FeSi75 fines fall directly into the metal bath and melt. The fines are of the same composition as the molten metal and do not influence the chemical balance of the furnace in any way.

CHARGING OF RAW MATERIALS

Theory

Quartzite, when charged through the electrode, finds its way directly to the crater, without influencing the conductivity of the charge. This happens instantly, while in conventional quartzite charging, it takes hours from the time the material is charged on top of the furnace, to the time it reaches the crater and reacts. This instant charging of quartzite introduces the possibility of controlling the chemical balance of the charge and thus operating the furnace more efficiently.

The influence of charging coke ($C_{(s)}$) directly to the crater is negative, according to the general model of the process mechanism. It is safe to conclude that the efficiency of the process will decrease if $C_{(s)}$ is partly fed directly to the crater. This conclusion is based on the assumption that $C_{(s)}$ does not accumulate, but reacts to $SiC_{(s)}$ and later to $CO_{(g)}$. If $C_{(s)}$ or $SiC_{(s)}$ accumulate in the crater the furnace will finally become un-operational.

The electrode consumption occurs mainly through *chemical reactions, arc erosion* and *propagation of cracks and splits* at the arc tip. It is possible that carbon charged through the hollow electrode can partly replace the carbon of the electrode in the chemical reactions and thus decrease the electrode consumption.

Quartzite fines

The charging of quartzite fines proved to be extremely difficult because the quartzite has a severe tendency to clog up the centre hole. As a result, it was impossible to charge quartzite fines to the crater in sufficient quantities and for sufficiently long periods of time to draw conclusions regarding how the charging of quartzite fines directly to the crater influences the FeSi75 process. It is impossible to present one "correct" explanation for the problems associated with the charging of quartzite fines. On the basis of observations from the experiments it is however possible to list some important factors which could well influence the clogging process. The main factors are:

- Fine particles have a lower melting point than particles of normal grain size because of higher concentration of impurities in the finer particles.
- The fraction of fine particles is increased because of crushing in the screw conveyors.
- The quantity of fine particles is increased when β-*quartz* is transformed to *cristobalite* and the volume increases 14.3% as a result. The surface layers of the particles explode and a higher number of fine particles is created.
- Quartzite in the liquid phase is viscous. Quartzite particles that melt on their way down the electrode hole may therefore get stuck on the wall instead of moving downwards.

Based on the factors listed above, the following mechanism is suggested for the clogging of the hole when quartzite is being charged. The smallest particles are warmed up very efficiently through thermal radiation and will reach the melting temperature. If they move close enough, a film of viscous quartzite is deposited on the electrode wall. This film gets thicker as other particles get stuck in the viscous film and melt. This process eventually leads to complete clogging-up of the hole. The most important factors that control this mechanism are the following: *The particle size*, as smaller particles reach the melting temperature higher up in the electrode, and *the purity* of the quartzite as impurities tend to lower the melting temperature. The clogging-problem is *very much enhanced* by the chrushing effect of the screw conveyors. The ratio of fine particles is much higher after the transport than before.

Coke powder

Experiments involving the charging of coke were few and limited to only few hours of charging each time, and data from the experiments is therefore limited. No practical problems were experienced with the charging of coke powder.

No immediate effect on the tapping of FeSi75 and the dust production was observed when up to 2.5 tons of coke was charged in approx. 5 hours. This indicates that the charging of coke powder to the crater does not have any *drastic* effect on the furnace operation. The holder position of the hollow electrode was, however, strongly affected. The quantity of charged coke powder through electrode 2 (Ch) is shown in Fig. 4, along with the holder positions of all electrodes. Also shown is the charging of coke powder and the charging of extra coke (C-x) and quartzite (Q-x) on the charge *surface* (the charging of extra coke or quartzite on the charge surface is used in order to adjust the electrode holder position). Fig. 4 shows that electrode 2 moves *upwards* during the charging. Shortly after the charging stops, the electrode moves *downwards* again.

The electrical conductivity of both *carbon* and *silicon carbide* is very high compared to the electrical conductivity of *quartzite*, at the high temperatures in the crater [3]. The observed upward motion of the electrode when coke powder is charged, could therefore be due to an increased electrical conductivity of the raw-material mix around the electrode as a result of increased density of coke or silicon carbide powder in the charge near the crater. This "long-time effect", however, disappears shortly after the charging stops and the electrode moves downwards again.

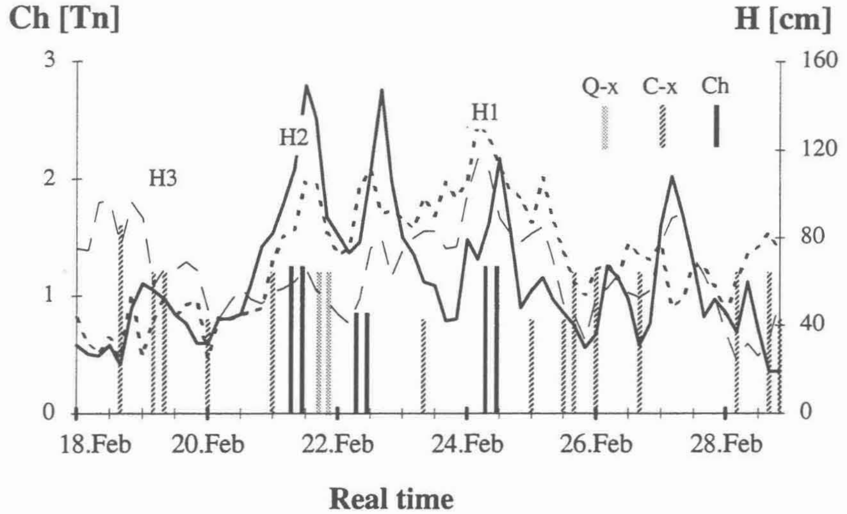

FIG. 4. Charging of coke powder (Ch) through electrode 2 and positions of electrodes (H1,H2,H3), charging of extra coke (C-x) and quartzite (Q-x) on the charge surface.

Conclusion

The charging of quartzite fines has proven to be very difficult, as the screw conveyors tend to chrush down the fines and thus increase the content of very small particles. There are no practical problems associated with the charging of coke powder. There are, however, strong indications that the charging of coke powder is negative for the furnace operation. This charging seems to increase the electrical conductivity of the *charge* near the electrode and the electrode moves *upwards* in the furnace as a result of this. This effect of the charging of coke powder on the electric conductivity of the charge is a *long-time effect* and should not be confused with *the short-time effect* on the arc resistance.

THE ARC RESISTANCE

Results from short-time measurements

In short-time measurements the automatic control system was disconnected and the effect of turning the charging of nitrogen and fines periodically on and off was studied. The time of one series was about 14 min and the period was 2 minutes, i.e. the charging was on for 1 minute and off for 1 minute.

The current (I) and voltage (U) during the charging of *coke powder* are shown in Fig. 5 i. The charging rate of coke powder was 20 kg/min in the charging periods. The figure shows that the charging of coke powder has a very strong effect on both voltage and current of electrode 2. The charging also affects the total furnace power as Fig. 5 ii demonstrates.

The short-time experiments showed that the injection of *nitrogen* and charging of *coke powder* influences the measured voltage and current of the hollow electrode in a significant way. The charging of *FeSi75* fines and *quartzite* fines, on the other hand, has a very small influence on the measured current and voltage.

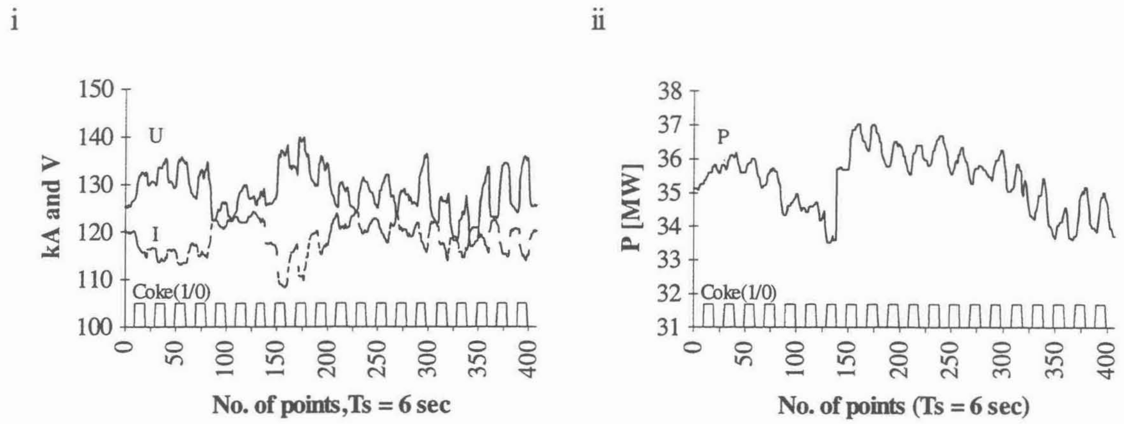

FIG. 5. Charging of *coke powder* and i. time series of voltage and current for electrode 2, ii. time series of measured total furnace power.

The results of the short-time measurements concerning electrode 2 are summed up in Table 2. Nitrogen was injected *continuously* in the case of *periodic* charging of fines and powder.

TABLE 2. An overview over results of short-time experiments.

	Nitrogen	FeSi75 fines	Quartzite fines	Coke powder
Flow rate	0.75 Nm^3/min (0.9kg/min)	30 kg/min	20 kg/min	20 kg/min
Change in U (V)	+2.74	+0.69	+0.92	+8.22
Change in I (kA)	-1.81	-0.8	-0.51	-5.26
Strong influence?	Yes	No	No	Yes

The last row in Table 2 is a general comment on the strength of the correlation between the injection/charging of gas/fines and the voltage and current. While the influence of *nitrogen* injection and charging of *coke powder* is strong, the influence of charging *FeSi75 fines* and *quartzite fines* is very small.

Entrainment in the electric arc

The difference in the measured influence of the different species on the voltage and current must be explained by different *entrainment* of the gas/particles in the plasma flow generated by the arc. The FeSi75 fines as well as the quartzite fines fall directly into the metal bath below the electrode, without contacting the arc. The arc voltage and current are therefore not directly influenced by the charging of FeSi75 and quartzite fines. The coke powder consists of much smaller particles than the FeSi75 and quartzite fines. Furthermore, the coke powder does not melt, but sublimates at a temperature level far above the temperature of the crater gas. It is therefore concluded that the coke powder only partly falls into the metal bath. A considerable part of the powder circulates in the crater, driven by the powerful plasma jet and exposed to the arc with the resulting "short-time influence" on its voltage and current.

Results of Arc Channel Model

An *Arc Channel Model* (ACM) [4] was used to estimate how the arc resistance is influenced by the injection of nitrogen and particles through the hollow electrode. It is assumed that the gas is heated to the arc temperature and the particles to the crater temperature. The model is utilised to simulate two cases, injection of nitrogen and combined injection of nitrogen and charging of FeSi75 fines. Two sets of simulations are made for each case, assuming 50% and 100% entrainment of the gas/particles in the plasma flow. The results of the model, combined with observations from the short-time measurements, indicate that only about 15% of the injected nitrogen is entrained in the plasma flow. Similarly, the model predicts that the degree of entrainment of the FeSi75 fines in the plasma flow is *very small.*

Non-rigid power grid

The observed ratio of voltage increase to current decrease remained inexplicable until it was realised that the power supply grid at Icelandic Alloys Ltd. plant at Grundartangi is *non-rigid*, i.e. the secondary voltage U_2 of the furnace transformer is not constant. Simulations using an equivalent single-phase circuit which includes the short-circuit impedance of the power grid have shown that a limited increase in the charge resistance, resulted by the injection of gas and particles through the hollow electrode, leads to an increase in the total furnace power, when the furnace control system is not connected. This is the result despite the fact that $\cos\phi>0.707$.

Conclusion

The charging of gas/particles through the hollow electrode leads to a decrease in the electrode current by *decreasing the electrical conductivity of the arc*. The control system of the furnace aims at keeping the electrode current constant by moving the electrodes up and down. The only influence of the charging on the electrical environment, when the control system is connected, will therefore be a *lower* holder position.

CRATER PRESSURE

Measurements of the crater pressures for *all three electrodes* indicate that these parameters contain interesting information regarding the state of the furnace craters. A known relation between stoking and dust production reflects that the furnace must be stoked regularly in order to sustain a satisfactory furnace operation and a low dust production [5]. Fig. 6 shows the relationship between pressures, *measured in all craters*, stoking and dust production for a typical stoking period. The pressure in all craters is shown (P1, P2 and P3), along with the density of silica fume in the smoke stack (Du) and the signal from the stoking car. The density of silica fume is very high during the first 7 minutes. At the same time, the measured pressure in all craters is low, at the highest 4 kPa in electrodes 1 and 2, but 2 kPa in electrode 3. The dust production decreases momentarily as stoking begins and the pressure increases in all craters. 10 minutes after stoking the dust production increases again and the crater pressure decreases at the same time. The figure indicates that the simultaneously measured pressures are *different* from crater to crater. *Changes* in the pressures occur, however, simultaneously for all craters, i.e. all crater pressures increase during stoking and decrease shortly after stoking.

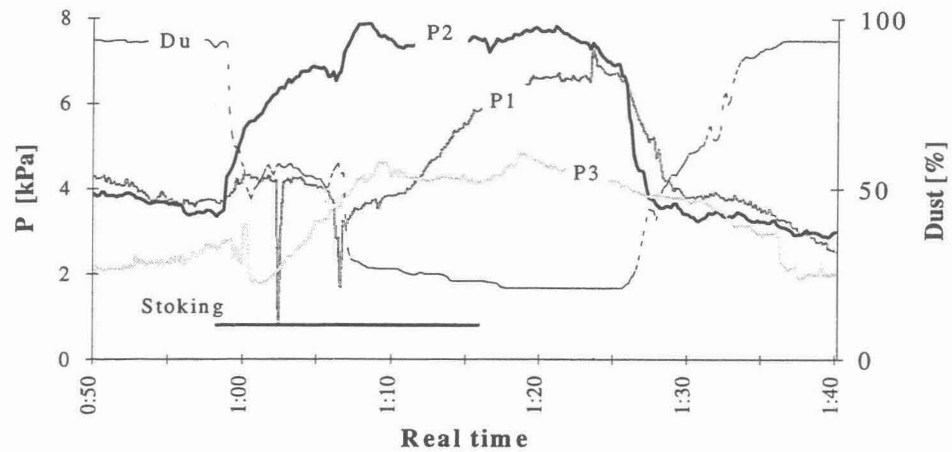

FIG. 6. Pressure in all craters (P1,P2,P3), stoking and dust production (Du) during a typical stoking period.

Fig. 7 shows a longer period for the pressure measurements in all craters. The figure shows the pressure in craters 1, 2 and 3 (P1, P2 and P3), sampled with a frequency of 2 minutes over a period of 8 hours. The figure indicates a strong relationship between the measured pressure in all three craters. This observation is confirmed by Table 3 which shows the symmetric matrix of correlation coefficients between the measured pressure (Pi) in all the electrodes.

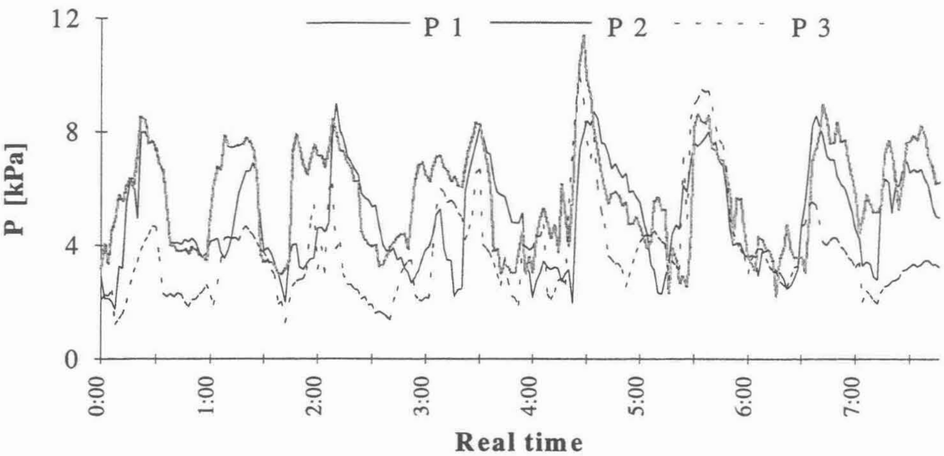

FIG. 7. Pressure measured simultaneously in all craters.

TABLE 3. Correlation coefficients between measured pressures in all craters.

correl.coeff. (r)	P1	P2	P3
P1	1	0.61	0.47
P2	0.61	1	0.51
P3	0.47	0.51	1

Fig. 6 shows that the simultaneously measured pressures are different from crater to crater. Fig. 7 and Table 3 show however that *changes* in the pressures occur simultaneously for all craters, i.e. all crater pressures increase when the furnace is stoked and decrease shortly after stoking. It is thus likely that all three craters are inter-connected, but only to a certain degree.

It is concluded that information regarding the operational condition of each crater and the surrounding charge can be obtained by measuring the pressure in each crater.

THERMAL STRESSES IN THE ELECTRODE

Four numerical models have been utilised in order to predict the influence of the operation of the hollow electrode on the thermal stresses in the electrode during a typical shut-down and start-up period.

- The *Hollow Electrode Temperature Profile Model* (TPM) [6] was developed in order to calculate the heat transfer from the electrode to the gas/particles in the central hole, based on the wall temperature distribution of the electrode hole.
- *ELKEM's two dimensional electrode temperature model* (ELKEM-D) [7] is utilised to calculate the temperature profile in the electrode, taking into account the heat transfer from the electrode to the gas/particles.
- *ELKEM's electrode thermal stress model* (ELKEM-T) [8] is utilised to calculate how the cooling of the electrode, as a result of the flow of nitrogen and particles, influences the thermal stresses in the baked part of the electrode during transient conditions (effect of cooling).
- The *ANSYS electrode thermal stress model* (ATM) was developed in order to calculate how the central hole itself influences the thermal stresses in the baked part of the electrode during transient conditions (effect of geometry).

By iteration between TPM and ELKEM-D, the steady temperature profiles in the electrode and the gas/particles flow are calculated, along with the corresponding heat extraction from the electrode by the material flow .

The numerical simulations with the TPM and ELKEM-D models indicate that the injection of gas and charging of material fines has a considerable cooling effect on the baked electrode around the centre hole. This result is supported qualitatively by measurements . The numerical simulations with ELKEM-T indicate that the maximum *axial tensile stress* in the electrode, during a typical shut-down and start-up period, is very much reduced as a result of the *cooling* caused by the flow of gas and particles through the centre hole. This reduction amounts to 28% in the case of nitrogen injection and 33% in the case of combined nitrogen injection and FeSi75 charging. Numerical simulations with the ANSYS model indicate that the modified geometry of the hollow electrode, i.e. the centre hole itself, has a very small, but positive, influence on the critical axial tensile stresses. The results indicate that the radial and tangential stress components are of the same magnitude as the axial stress. The maximum radial and tangential tensile stresses are 59% of the maximum axial tensile stress in the case of a solid electrode.

Electrode breakages are among the most serious problems in the operation of FeSi75 furnaces. Hard breakages are most common, mainly caused by thermal stresses in the electrode during shut-down and start-up of the furnace. It is concluded that the operation of Söderberg electrodes with centre pipes *increases the operational safety* in the FeSi75 production, by reducing the risk of hard breakages [9].

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