

# Energy consumption during HCFeCr-production at Ferbasa

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## ABSTRACT

*Improved understanding of energy distribution in the furnace and of the effect of different parameters on specific energy consumption is important when means to reduce energy consumption are evaluated.*

*A staged energy and material balance has been calculated for HCFeCr production at Ferbasa based on the charge mixture in February 2011. In the main example, the calculated total energy consumption per ton of alloy is 3585 kWh/ton of alloy. Losses in power supply and heat losses from furnace shell are not included. This is assumed to be within the normal range for HCFeCr production. 73 % of the energy is consumed at temperatures between 1200 °C and 1700 °C, in the coke bed zone in the furnace. Total consumption and consumption in the different zones is similar to values calculated earlier for Elkem Rana.*

*The effect on energy consumption of different parameters has been calculated based on the results from this balance. Here a theoretical charge mixture based on a single Brazilian chromite ore, Jacurici, was used. The effect of variations in temperature and composition of both off gas and slag were calculated as well as the effect of varying Si-content in the produced alloy. Drying and preheating are possible methods to reduce energy consumption and effect on energy consumption of moisture and raw material temperature have thus been calculated for various cases. Energy distribution in the furnace is described by a staged energy balance.*

## 1 INTRODUCTION

High Carbon Ferrochromium, HCFeCr is an important alloy for production of stainless steel. It is mainly produced by reduction of chromite ores by carbon in Submerged Arc Furnaces (SAF). The produced alloys contain 45-75 % Cr depending on ore composition and around 0-10 % Si depending on customer specification. Production of HCFeCr alloy is energy intensive and requires around 3500 – 4000 kWh/ ton of alloy. The energy consumption and chromium yield vary with product composition and ore type [1] as well as with furnace operation. Specific energy consumption can be reduced by pretreatment of the ores [2]

In this work the effect on energy consumption by changing ore type and the possibilities for reducing specific energy consumption at the Ferbasa plant in Brazil has been investigated. Ferbasa produces HCFeCr in 5 furnaces with a size from 18.5 to 24 MVA [3]. The chromium sources have traditionally been two local ores, Comisa and Jacurici. Both lump ores and concentrates from these have been used. The concentrates are sintered before they are fed to the furnaces. Coke is used as reductant. A mixture of the two ores has been used in the charge fed to the furnace. A staged heat and material balance based on industrial data from use of this mixture has been calculated to gain more knowledge about the energy distribution in the furnace. Currently a change towards use of only Jacurici ore in the charge mixture is evaluated. The effect of various parameters on energy consumption with use of only Jacurici ores has therefore been evaluated by theoretical calculations.

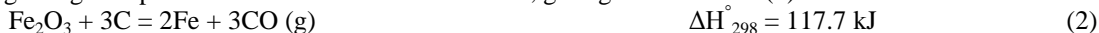
The raw materials used for ferrochromium production are chromite ores, fluxes and carbon. When the charge mix of chromium sources, fluxes and carbon is heated in a reducing atmosphere, several chemical reactions will occur. At low temperatures the water will evaporate, consuming 0.63 kWh/kg of water (at 100 °C) according to reaction (1).



Some chromite ore contains hydrated water; most often serpentine that decomposes around 800 °C. Produced H<sub>2</sub>O reacts with CO to CO<sub>2</sub> which at these temperatures reacts further by the energy demanding Boudouard reaction with C to CO<sub>2</sub>. Produced H<sub>2</sub> content is seen in the off-gas analysis. The total reaction is summed up in (2).

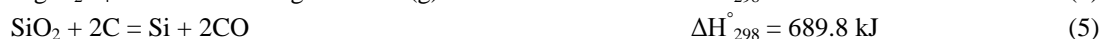


In chromite ores containing free hematite, at temperatures between 800 °C and 1200 °C iron may react with ascending CO-gas in parallel with the Boudouard reaction, giving total reaction (3)



At higher temperatures above 1200 °C, the chromite spinel will be reduced. The ore mineral is a solid solution between the spinels FeCr<sub>2</sub>O<sub>4</sub>, MgCr<sub>2</sub>O<sub>4</sub> and MgAl<sub>2</sub>O<sub>4</sub> which are mixtures of the oxides Cr<sub>2</sub>O<sub>3</sub>, FeO, MgO and Al<sub>2</sub>O<sub>3</sub>. Total energy consumption for the industrial case is calculated based on reduction of the separate spinels while the comparisons of different cases are based on reduction of the different oxides. These simplifications induce some inaccuracy. But these are as discussed below assumed to be lower than the inaccuracies induced by the calculation of amount of

each spinel in the different theoretical cases Both the spinels and the oxides are reduced with carbon by the following reactions



Both chromium and iron oxide can be partly reduced to metal in solid state in the charge bed in the upper part of the furnace or by separate pre-treatment outside the furnace. Reduction of the remaining Fe and Cr oxides together with magnesiachromite,  $\text{MgCr}_2\text{O}_4$  will take place in the coke bed where particles of chromite dissolve in the liquid slag phase and Fe and Cr oxides is reduced from the slag. In the cases studied here, dissolution of chromite into in the slag was slower than reduction from it and the slag had a relatively low content of Cr and Fe [Ошибка! Закладка не определена.]. The energy needed for melting of the oxides and alloys comes in addition to the energy needed for reduction.

Drying, calcination and preheating of chromite ores outside the furnace have been reported [Ошибка! Закладка не определена.] to reduce consumption of electrical energy in the furnace down to 1.7 MWh/ton alloy compared to the traditional consumption of around 3.5 MWh/ton. The effect will vary from case to case depending on characteristics of raw materials and of furnace operation. Pelletising and prereluction units are installed on several industrial furnaces. The effect of drying and preheating are discussed below

## 2 CALCULATIONS

Energy consumption during HCFer production at Ferbasa has been calculated by two different approaches. The first case is based on industrial data from February 2011 and the charge mixture and raw materials used that month. Energy and material distribution between the different zones in the furnace as well as total energy consumption is calculated. In the second study the effects on specific energy consumption of different parameters were investigated by comparing different scenarios with a base case and comparing the relative effects of the parameters.

HSC chemistry software from Outotec was used for calculating the energy consumption. In the first approach HSC 6.1 was used while HSC 7.1 was used in the second in order to have access the most updated databases Energy losses as heat loss and losses in bus bar are not included. They normally account for around 20 % of total consumption, so the calculated values are round 80 % of what will be experienced industrially.

The enthalpy for dissolution of carbon and the other mixing enthalpies in the alloy are omitted in the balance. The enthalpy of heating and melting of slag is calculated by assuming that the pure oxides are heated up to 1400 °C where they melt, and that all mix enthalpies are zero.

### 2.1 Staged material energy balance for February 2011

Specific energy consumption and staged material and energy balance is calculated based on consumption and production figures for Ferbasa in February 2011 given in Table 10 to Table 12.

**Table 10** Raw materials used by Ferbasa February 2011

Material	Kg/ton alloy	% Cr <sub>2</sub> O <sub>3</sub>	% FeO	%SiO <sub>2</sub>	%Al <sub>2</sub> O <sub>3</sub>	%CaO	%MgO	% C fix
Lump Jacurici ore	1391	38.3	15.7	10.8	14.3	0.5	15.0	
Lump Comisa ore	106	38.9	17.4	9.9	11.4	0.4	17.0	
Comisa concentrate	36	38.8	28.4	7.4	7.6	0.2	13.5	
Chromite Sinter	987	36.4	21.9	12.9	10.1	1.0	13.5	
Recovery raw material	44	31.2	20.4	10.2	11.8	3.3	14.5	6.8
Quartz	290	0.0	0.5	98.5	0.1	0.0	0.0	
Mg rich flux	109	19.0	12.4	27.0	15.7	5.1	19.8	
Coke	512							84.1
Sum kg	3474	9314	4620	5782	3175	222	3709	3805

**Table 11** Slag produced by Ferbasa February 2011

kg/ton alloy	% Cr <sub>2</sub> O <sub>3</sub>	% FeO	% SiO <sub>2</sub>	% Al <sub>2</sub> O <sub>3</sub>	% CaO	% MgO
1802	9.0	2.1	35.6	21.0	1.5	28.8

**Table 12** Alloy produced by Ferbasa February 2011

	% Cr	% Fe	% Si	% C
HCrFeCr	55.42	32.33	3.68	7.57

The amount of different minerals is calculated by a mass balance based on amount and analysis of raw materials and products. Tonnage of slag can be calculated from slag analysis by assuming that all Al<sub>2</sub>O<sub>3</sub> and MgO from the raw materials end up in the slag. Tonnage of the other elements can then be found from their percentage. Since the slag contains some alloy with Fe and Cr, this amount will deviate from the amount calculated by difference. For Ferbasa the deviation is 2-5 %. Since the amount of raw materials and products and the chemical analysis of these are considered to be most accurate, these are used in the calculations and the content in slag is assumed to be the difference between contents in raw materials and in products.

The amount of each of the minerals is calculated by the following method: It is assumed that all Fe in slag exists as FeCr<sub>2</sub>O<sub>4</sub> and that remaining chromium content in slag is found in MgCr<sub>2</sub>O<sub>4</sub>. This is all the content of MgCr<sub>2</sub>O<sub>4</sub> in the raw materials. Remaining chromium in the raw materials is found in FeCr<sub>2</sub>O<sub>4</sub>. Amount of FeO left, is assumed to be FeO while remaining amount of MgO is assumed to exist as MgO or in other MgO minerals. The amount of other minerals is not calculated and only the chemical compounds are used in the calculation. This will have minimal influence on the calculation. It must be mentioned that the calculation procedure will be different when there is more (in mol) Cr<sub>2</sub>O<sub>3</sub> than FeO in the raw materials.

The amounts of various compounds in the raw materials, based on this calculation, are shown in Table 13.

**Table 13** Amount of chromite minerals and oxides in raw materials and slag

Compound	kmol/ton alloy	kg/ton alloy	kmol in slag	kmol in gas	kmol reduced
FeCr <sub>2</sub> O <sub>4</sub>	6,28		0,95		5,33
MgCr <sub>2</sub> O <sub>4</sub>	0,15		0,15		0
Fe <sub>2</sub> O <sub>3</sub>	0		0		0
FeO	0,32		0		0,32
MgO	9,50		9,50		0
SiO <sub>2</sub>	10,09		8,78		1,31
CaO	0,42		0,42		0
Al <sub>2</sub> O <sub>3</sub>	3,26		3,26		0
C	33,25		0	26,94	6,31*

\* C dissolved in produced alloy

A staged energy balance is calculated based on method from earlier work [Ошибка! Закладка не определена.], the input data described above and by use of the program and database in HSC 6.1 from Outotec.

The furnace is divided in to 4 different zones

25 -300°C:

Zone 1: Drying and heating.

Burning of CO. Drying. No supply of electrical energy.

300 -1000°C:

Zone 2: Heating.

Heating to 1000 °C. Reduction of hydrated water

1000 -1200°C:

Zone 3: Solid state reduction.

Reduction of iron oxide not bound in chromite

1200 -1400°C:

Zone 4: Reduction to liquid alloy.

Iron chromite is reduced to liquid alloy and chromium oxide.

1400 -1700°C:

Zone 5: Liquid state reduction.

Magnesia chromite and chromium oxide are reduced to alloy. Liquid slag is formed and some silica is reduced to silicon in the alloy.

Burning of CO-gas to CO<sub>2</sub> near the top of the charge produces enough energy to evaporate the moisture in the charge and to heat it to 300 °C. Neither the temperature nor the amount of CO<sub>2</sub> in the off-gas from Ferbasa is known.

The off gas temperature is assumed to be 450 °C and the amount of produced CO<sub>2</sub> is adjusted so no extra energy is required in this zone.

Structural water in the minerals is normally assumed to be reduced around 700 °C and will then contribute to H<sub>2</sub> in the off-gas [Ошибка! Закладка не определена.]. Since neither amount of crystalline water in the ore nor amount of H<sub>2</sub> in the off-gas at Ferbasa is known, this is calculated from the carbon balance. Amount of carbon in the raw materials that is not consumed by other reactions is assumed to be used for reduction of crystal bound water. This is a very rough estimate since carbon consumed by Boudouard reaction is not included, but it is used since gas analysis at HCFeCr production at Elkem Rana[Ошибка! Закладка не определена.] indicated that very little C was consumed for CO<sub>2</sub> production.

It is assumed that there is no trivalent iron in the charge mixture. Industrial excavations [Ошибка! Закладка не определена.] have shown that iron is produced at high levels in the furnace. It is here assumed that all FeO is reduced in zone 3 between 1000 °C and 1200 °C. CO<sub>2</sub> produced by reduction with CO-gas will at these temperatures react with carbon to CO.

A liquid alloy can exist above approximately 1200 °C. Iron chromite is then assumed to be reduced to liquid Fe and to Cr<sub>2</sub>O<sub>3</sub>. A liquid slag is formed around 1400 °C. The maximum temperature in the furnace is assumed to be 1700 °C. Between these temperatures, in zone 5, the remaining chromite is reduced, the slag melts and SiO<sub>2</sub> in the slag is reduced to Si in the alloy. Carbon dissolves in the alloy until the final carbon content is reached. The heat exchange between the ascending off gas and the descending charge is included in the balance.

## 2.2 Comparison of different scenarios

The effects on energy consumption of various parameters have been investigated by calculation of different scenarios by HSC 7.1. A base case has been defined, and the change in specific energy consumption for the scenarios has been compared with the base case. In all cases Jacurici ore is the only chromium source in all scenarios. Its composition is given in Table 10. The main parameters in the base case can be seen in Table 14. Parameters used in the different scenarios are described together with the results in section 4.

**Table 14** Main parameters in base case

Ore	Raw material temp °C	% H <sub>2</sub> O in charge	Off gas temp °C	% SiO <sub>2</sub> in slag	% Cr <sub>2</sub> O <sub>3</sub> in slag	% Si in alloy
Jacurici	25	0	300	35	10	4.2

Calculations in the base case are in addition based on no prereduction of the ores. It is also assumed that all iron is bound in the chromites as FeO. Changes in carbon content in the alloy due to varying Si content are not included and in all scenarios 7.5 % C in the alloy is used. In order to vary few parameters within each scenario and thereby clarify the effects better, the calculations are based on the content of oxides in the slag instead of the content of chromite minerals in the slag. Content of oxide compounds instead of content of chromite minerals are therefore also used for the raw materials including Jacurici ore. This means that energy needed for breaking up of the minerals is not included. This will give lower energy consumption than in the industrial cases, but differences between the scenarios are comparable and will be more general.

Amount of slag and alloy and their percentage of the different components are in principle calculated by the same method as for the Staged material and energy balance based on analysis of raw materials and products. It is assumed that all Al<sub>2</sub>O<sub>3</sub> and MgO from the raw materials end up in the slag. % FeO in the slag is assumed to be bound in partially reduced chromite particle and from earlier investigations of partially reduced chromite, mol ratio of Fe/Cr in slag is estimated to be 0.5\*Fe/Cr mol ratio in chromite. When % Cr<sub>2</sub>O<sub>3</sub> and % SiO<sub>2</sub> in the slag and %Si and % C is given, amount of slag, alloy and required amount of each of the raw materials can be calculated.

## 3 STAGED HEAT AND MATERIAL BALANCE

The resulting staged material and energy distribution is shown in Figure 28. Amount of the compounds are shown as kmol per ton of alloy. Temperatures of charge in to each zone are shown in the left column while mol of gas and gas temperatures are shown in the right column.

The energy requirement is 3585 kWh/tonne when the energy losses in transformers, conductors and electrodes and the heat losses from the furnace shell are disregarded. If the sum of thermal and electrical efficiency is 85 %, the total registered energy consumption will be about 4200 kWh/tonne alloy. The specific energy consumption at Ferbasa seems to be in the normal range for HCFeCr production and the distribution is comparable to a distribution calculated at Elkem Rana in 1996[Ошибка! Закладка не определена.].

Most of the energy, 73 %, is consumed between 1200 °C and 1700 °C in zones 4 and 5, at the top of the coke bed and in the coke bed. Here energy is supplied to the furnace as ohmic heating by the current through the cokebed. Energy

supply to zone 2 with its relatively large energy consumption is not clear. The calculated consumption is based on analysed crystalline water in raw materials and analyses of H<sub>2</sub> in the off gas. If the reaction takes place with CO instead of C at lower temperatures than assumed here, the energy consumption in this zone will be lower.

Charge in		Gas out
25°C	$3,39 \text{ H}_2\text{O(l)} = 3,39 \text{ H}_2\text{O(g)}$ $1,55\text{CO} + 0,78 \text{ O}_2 = 1,55\text{CO}_2$	<b>450°C</b> 25,5 CO
300°C	$2,7 \text{ H}_2\text{O} + 2,7 \text{ C} = 2,7 \text{ H}_2 + 2,7 \text{ CO}$ <b>778 kWh</b>	<b>1000°C</b> 27,0 CO
1000°C	$0,32\text{FeO} + 0,32\text{C} = 0,32 \text{ Fe} + 0,32\text{CO}$ <b>169 kWh</b>	<b>1200°C</b> 24,3 CO
1200°C	$5,33 \text{ FeCr}_2\text{O}_4 + 5,33 \text{ C} = 5,33 \text{ Cr}_2\text{O}_3 + 5,33 \text{ Fe} + 5,33 \text{ CO}$ <b>530 kWh</b>	<b>1400°C</b> 24,0 CO
1400°C	$5,33 \text{ Cr}_2\text{O}_3 + 16\text{C} = 10,66 \text{ Cr} + 16 \text{ CO}$ $1,31\text{SiO}_2 + 2,62\text{C} = 1,31\text{Si} + 2,62 \text{ CO}$ $6,31 \text{ C} = 6,31 \text{ C}$ $8,8 \text{ SiO}_2 = 8,8 \text{ SiO}_2(\text{l})$ $9,5\text{MgO} = 9,5\text{MgO}(\text{l})$ $3,26 \text{ Al}_2\text{O}_3 = 3,26 \text{ Al}_2\text{O}_3(\text{l})$ $0,42\text{CaO} = 0,42 \text{ CaO} (\text{l})$ <b>2108 kWh</b>	<b>1700°C</b> 18,62 CO
1700°C	<b>Total 3585 kWh</b>	

Figure 28 Staged heat and energy balance for Ferbasa February 2011

#### 4 COMPARISON OF ENERGY CONSUMPTION IN DIFFERENT SCENARIOS

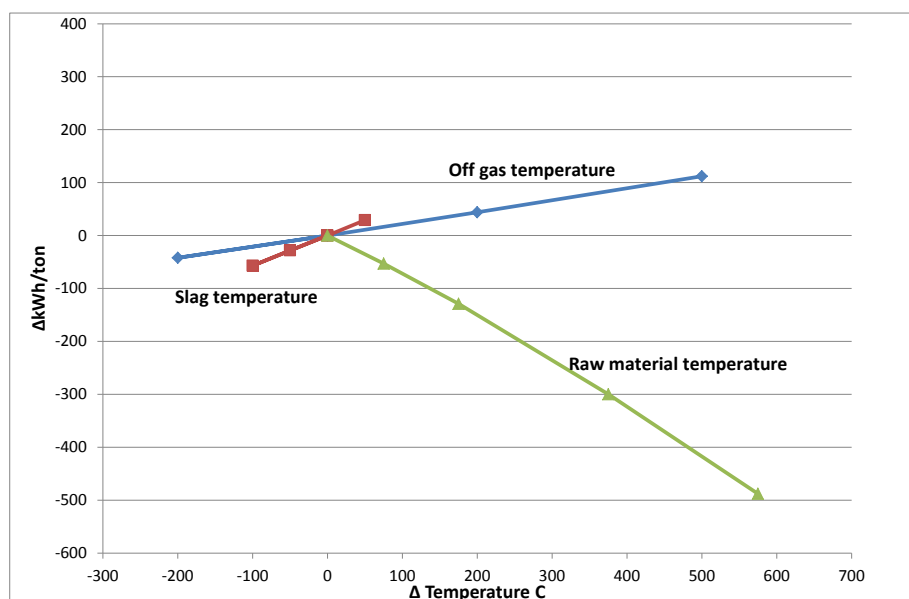
The effects on energy consumption in the furnace were investigated for varying off-gas temperatures. Slag temperatures, raw material temperatures, % Si in alloy, % Cr<sub>2</sub>O<sub>3</sub> in slag and % H<sub>2</sub>O in charge mixture. Values for the variables in each scenario and the resulting energy consumptions are given in Table 15.

For each scenario only one variable is changed and the results are compared with a base case where the energy consumption is 3440 kWh/ton. In this case raw materials with zero moisture are fed to the furnace with a temperature of 25 °C, gas leaves the furnace top with a temperature of 300 °C, and slag with 10 % Cr<sub>2</sub>O<sub>3</sub> is tapped from the furnace at a temperature of 1700 °C. Slag/alloy ratio is 1.42. Produced alloy contains 4.2 % Si. Jacurici ore is the only chromium source in all cases. When % Si or % Cr<sub>2</sub>O<sub>3</sub> varies and all other parameters are kept constant, the slag/alloy ratio will vary.

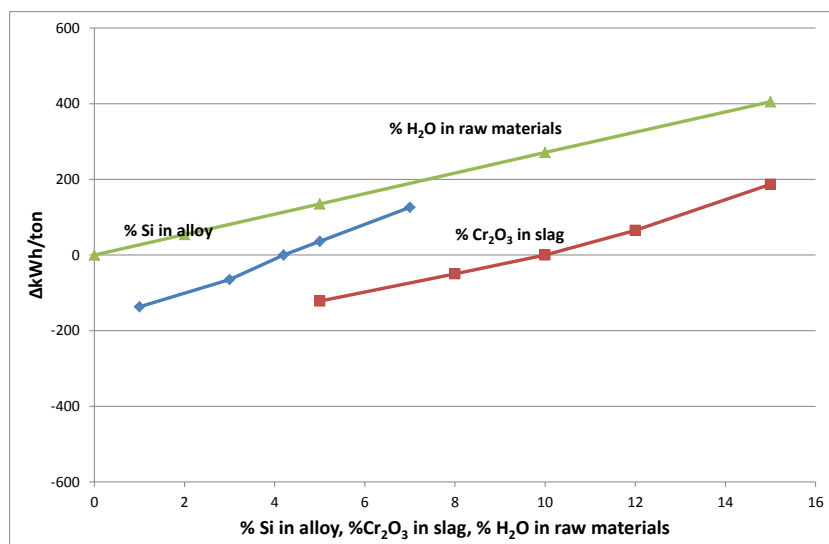
**Table 15** Effect on specific energy consumption in the furnace of various parameters

Scenario	Base case	1	2	3	4	5
<b>Off gas temperature</b>	300	100	300	500	800	
kWh/ton	3440	3398	3440	3484	3552	
Δ kWh/ton	0	-42	0	44	112	
<b>Slag temperature</b>	1700	1600	1650	1700	1750	
kWh/ton	3440	3383	3412	3440	3469	
Δ kWh/ton	0	-57	-28	0	29	
<b>Raw material temp</b>	25	100	200	400	600	
kWh/ton	3440	3387	3311	3140	2952	
Δ kWh/ton	0	-53	-129	-300	-488	
<b>% Si in alloy</b>	4.2	1	3	4.2	5	7
kWh/ton	3440	3303	3375	3440	3476	3566
Δ kWh/ton	0	-137	-65	0	36	126
Slag/alloy	1.42	1.47	1.44	1.42	1.41	1.37
<b>%Cr<sub>2</sub>O<sub>3</sub> in slag</b>	10	5	8	10	12	15
kWh/ton	3440	3318	3390	3440	3505	3627
Δ kWh/ton	0	-122	-50	0	65	187
Slag/alloy	1.42	1.21	1.33	1.42	1.53	1.72
<b>%H<sub>2</sub>O</b>	0	2	5	10	15	
kWh/ton	3440	3494	3575	3711	3845	
Δ kWh/ton	0	54	135	271	405	

The effect of variations in temperatures is shown graphically in Figure 29 while the variations in analysis are shown in Figure 30. The vertical scale is the same in both figures so the resulting changes in specific energy consumptions can be compared directly. The deviation from a straight line for % Si in alloy and % Cr<sub>2</sub>O<sub>3</sub> in slag are a result of the variation in slag/alloy ratio in these calculations.



**Figure 29** Variation in kWh/ton by varying temperatures of raw materials, off gas and slag during HCFer production in a Submerged Arc Furnace (SAF)



**Figure 30** Variation in kWh/ton by varying values of %H<sub>2</sub>O in raw materials, % Cr<sub>2</sub>O<sub>3</sub> in slag and % Si in alloy during HCFerCr production in a Submerged Arc Furnace (SAF)

The calculations show that changes in the different variables can have a major impact on the energy consumption in the furnace. Slag temperature has the largest relative effect; a decrease in slag temperature from 1700 °C to 1600 °C will reduce specific energy consumption by 57 kWh. But since slag temperatures can only be varied within a relatively narrow interval, other parameters will have a larger impact on total energy consumption.

Energy consumption will vary with product quality. An increase in % Si in alloy from 4.2 % Si as in the base case to 7 % Si requires 126 kWh more per ton alloy produced if all other parameters are kept constant. This is a consequence of the relatively high ΔH for Si reduction.

Parameters that are affected by furnace operation or use of charge mix will influence the energy consumption. When the off-gas temperature decreases, less energy is lost in the off-gas. A decrease in off-gas temperature from the base case value of 300 °C to 100 °C will decrease energy consumption by 42 kWh. A reduction of % Cr<sub>2</sub>O<sub>3</sub> in the slag from 10% to 5 % reduces specific energy consumption by 122 kWh/ton. The reduced energy consumption is mainly a result of reduced slag/alloy ratio. Reduced slag temperature, will decrease the energy losses through the slag. Due to the high temperature, the effect of changes is larger than, for instance, changes in off-gas temperature. But slag temperature can only vary within a limited range. A reduction in slag temperature from base case value of 1700 °C to a value of 1600 °C that might be below the acceptable will reduce specific energy consumption by 57 kWh/t. If we look at the accumulated effect of these changes we will have a new case with 100 °C off-gas temperature, 1600 °C slag temperature and 5 % Cr<sub>2</sub>O<sub>3</sub> in the slag and a total energy consumption of 3219 kWh/ ton. This is 221 kWh/ ton lower than in the base case where off-gas temperature is 300 °C, Cr<sub>2</sub>O<sub>3</sub> in the slag is 10 % the slag temperature is 1600 °C and the energy consumption is 3440 kWh/ ton. The difference in energy consumption between these two cases is thus only 6.4 % although the operational parameters are relatively different

Properties of raw materials will also affect energy consumption. In the base case it is assumed that there is no moisture in the raw materials. Most raw materials contain some moisture varying with type, size, porosity and how they are handled and stored. Use of raw materials with in total 10 % moisture will increase energy consumption in the furnace by 271 kWh/ ton compared with the base case. This also means that drying of raw materials with 10 % moisture will reduce energy consumption by 271 kWh/ ton. The parameter that can contribute most to the energy consumption is heating of the raw materials. If they are heated from 25 °C, the temperature in the base case, to 600 °C, energy consumption in the furnace will decrease by 488 kWh/t. The total effect of drying and heating of the raw materials is a reduction of 759 kWh/ton compared with the base case but with 10 % moisture. The energy consumption is then decreased from 3711 kWh/ton to 2952 kWh/ton. Pretreatment of the raw materials is hence a method that can give a large reduction of energy consumption in the furnace. Such a pretreatment of the raw materials requires energy. Since no heating method has 100 % energy efficiency it will require more energy than can be gained in the furnace. But if energy that has no other usage is utilised, it will have positive impact. At most smelters there are several sources of low temperature heat streams and other energy sources that can be possible to utilise for drying and preheating. This can for instance be heat in cooling water or heat in off gas. To reach high temperatures such as 600 °, other sources must be used in addition. This can be electrical energy or burning of various carbon sources or the more environmental friendly alternative of burning of CO- gas.

Production of HCFerCr generates CO- gas with high energy content. In closed furnaces, the off-gas can be captured and the energy in the CO in the off gas can be utilised. Production of 1 ton of HCFerCr with the conditions de-

scribed in the base case will generate 565 Nm<sup>3</sup> CO gas with a temperature of 300 °C. Burning of this amount of CO gas with O<sub>2</sub> at 25°C, followed by cooling to 100 °C, will generate 2018 kWh. This is more energy than required for drying and further preheating to 600 °C of the raw materials needed to produce one ton of HCFeCr.

The staged heat and material balance were calculated based on content of the chromite minerals, FeCr<sub>2</sub>O<sub>4</sub> and MgCr<sub>2</sub>O<sub>4</sub> while the scenarios are calculated based on the compounds FeO, MgO and Cr<sub>2</sub>O<sub>3</sub>. Comparison of the two cases, shows that calculations based on compounds instead of minerals does not introduce a significant error. When the staged balance from 2011 was calculated based on compounds, total energy consumption was 3598 kWh/ton, a difference in only 13 kWh/ton or 0.36 % less than the base case. This is a lower variation than expected, due to inaccuracy in the method of calculation of mineral content. The difference includes also possible changes in the data base by using an updated version of HSC.

The difference between the charge mixture used in 2011 and the base case with only use of Jacurici ore was investigated by calculating the case from 2011 with the same assumptions that were used in the base case. This is no moisture in the raw materials, no crystal bound water and an off-gas temperature of 300 °C. The case from 2011 then had a specific energy consumption of 3479 kWh/ton e.g. 106 kWh/ton lower than when the industrial data were used in the calculations. Energy consumption calculated with the simplified calculation method was thus only 3% lower than the calculation based on the industrial data. The charge mixture in the base case with only Jacurici ore had an energy consumption of 3440 kWh/ton while the charge mixture from 2011 had when the same calculation method was used, an energy consumption of 3479 kWh/ton. The two charge mixtures hence had with the assumptions used here, approximately the same energy consumption. Effects of the different ores on operational parameters as Cr<sub>2</sub>O<sub>3</sub> in slag and off-gas and slag temperature are not included in the calculation. Such parameters may as discussed above have a major effect on energy consumption and must be taken into account when industrial use are discussed.

## 5 CONCLUSIONS

Calculations of theoretical energy consumption in different scenarios show that energy consumption in HCFeCr production can be reduced by different methods. The most actual of these are

- Reduced chromium content in slag. If the content of chromium oxide is reduced from 10% to 5% in the described base case, specific energy consumption will be reduced by 122 kWh/ton
- Reduced off-gas temperature. If the off-gas temperature at the charge top is reduced from 300 °C to 100 °C, specific energy consumption is reduced by 42 kWh/ton
- Preheating and drying of raw materials. Drying of raw materials with 10 % moisture and further preheating to 600 °C reduces specific energy consumption in the furnace by 759 kWh/ton. Total energy consumption will increase since heating of the raw materials cannot be done with 100 % efficiency. If not otherwise energy sources are utilised, preheating can have a positive impact on economy and on environmental footprint of the production.
- Prereduction of Chromite ore will further reduce energy consumption. The effect is not calculated here.
- Burning of CO in the off-gas will generate more than 2000 kWh/ ton of alloy. This can either be used inside the plant or converted to electricity. In both cases, the total energy consumption of the plant and its environmental footprint is reduced.

A staged heat and material balance shows that nearly 75 % of the energy is consumed at temperatures above 1200 °C, e.g. at the top of and in the coke bed

## 6 References

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