INFACON 7, Trondheim, Norway, June 1995
Eds.: Tuset, Tveit and Page
Publishers: FFF, Trondheim, Norway

Estimating and Comparing the Energy Consumption and Energy Losses for Ferrosilicon Furnaces

Senior Research Engineer, Dr.ing Sverre Inge Heimdal
Norwegian Marine Technology Research Institute[1]

ABSTRACT

Efficient energy consumption is vital for all energy demanding production and is one of the most important parameters defining the competitive position of ferrosilicon producers. From the perspective of economic modelling, this should imply elaborated models including all relevant elements necessary for supporting qualified reasoning about energy efficiency. Reality, however, is different. Evaluation of furnace productivity is usually based on empirical productivity ratios or simple theoretical models.

This paper presents a refined furnace energy model defining specific energy consumption as a function of silicon yield, a furnace load indicator and two parameters representing fixed and variable energy losses. The specific energy model may develop into an important instrument for product costs modelling and calculating the marginal value of changes and modifications influencing on energy consumption.

Empirical results based on data from 4 ferrosilicon furnaces support the suggested model structure. Calculations show that the difference in specific energy consumption between furnaces at the same level of silicon yield may be substantial. The results also illustrates the necessity of correcting for differences in furnace characteristics when specific energy consumption is used as a measure of furnace performance.

1. INTRODUCTION

Energy efficiency is essential for all producers seeking a competitive position within the ferrosilicon industry. Although both capital costs and costs for raw materials often exceed energy costs, energy efficiency has always been in focus since minimal energy consumption compared to produced amount of metal also is used to characterise furnace performance. Ratios at low levels also imply efficiency on raw material consumption and indicate a furnace operating close to maximum capacity.

---

[1]The material presented in this paper is based on research performed as a research schollar at the Department of Economics, The Norwegian Institute of Technology and is previously reported in a Dr.ing thesis defended in June 1991[1]. Necessary data are most kindly made available by the Elkem Company.

The search for the most efficient energy consumption possible will have to pass many stages. First of all it is essential to know the absolute minimum level obtainable. Secondly, the necessary understanding for making the right search for new solutions must be established. The key to this insight is probably the understanding of energy losses. Energy losses are significant compared to total energy consumption and are fluctuating due to changing operating conditions.

This paper will present a model describing the energy consumption in a ferrosilicon furnace. The model defines energy efficiency in terms of specific energy consumption as a function of silicon yield, furnace load and two energy loss parameters. Parameter estimates indicating energy loss for 4 furnaces will be presented, and the model will be used to demonstrate and explain the difference in energy efficiency between the furnaces.

The model will be tested in two versions. The first version is based on the ordinary silicon yield which is the ratio of silicon in produced metal to the amount of silicon in consumed raw materials. The second version applies an alternative silicon yield defined as the ratio of silicon in produced silica dust to the amount of silicon in produced metal. This ratio of produced silicon represent an alternative silicon yield which is not influenced by the difference between reduced silicon and charged silicon which in practice is very difficult to measure.

The rationale for developing this model has first of all been economic modelling. Empirically tested and verified models describing energy consumption will represent an important part of advanced ferrosilicon production cost calculations. More important is, however, that the model may be transformed to calculate marginal changes in energy consumption following marginal changes in silicon yield, furnace load or average furnace down-time. The model may thus contribute to qualified estimates about the potential value of changes in raw material mix or changes which influence on operating conditions.

An additional motivation for developing the model has been the ability to explain variations in furnace performance between different furnaces and between time periods for the same furnace. Models isolating the effect of silicon yield fluctuations and defining the minimum specific energy consumption possible will be helpful instruments for systematic comparisons aiming at improving economic performance. Instruments which include both metallurgical and economic reasoning have up to now been rather simple or totally missing.

2. ENERGY LOSSES

The sources of energy for producing ferrosilicon is electric energy and chemical energy released by the formation of CO and CO_2 following the reduction of SiO_2. The net energy requirement, equivalent to the consumption of <u>electric</u> energy is usually referred to as energy consumption. Based on existing knowledge about the ferrosilicon process, it is possible to calculate necessary electric energy to run the process. The calculations depend on assumptions about temperature on elements entering and leaving the furnace. Comparisons between theoretical electric energy requirements with figures on industrial consumption show that the existing furnace technology require electric energy consumption at levels 10 - 15 % above the theoretically calculated levels.

There are different ways of implementing this observation in economic models for ferrosilicon production. Most common is to assume fixed energy consumption ratios which implies that energy consumption and energy losses are unaffected of furnace performance. This simple model support the view of ferrosilicon production as a stochastic process and give few opportunities to calculate the value of improvements.

Other models describe net energy consumption as a function of silicon yield. An advanced model of this type is developed by Schei [2]. The specific energy consumption ratio for silicon metal is presented as follows:

$$H_{Si} = e\left(\frac{8{,}10}{Y} + 0{,}11\right) \quad (1)$$

The unit is [MWh/tonne] and the model parameters and variables have the following definitions:

- H_{Si} - The ratio of electric energy consumption to produced silicon
- e - Furnace efficiency parameter ($e \geq 1$)
- Y - Silicon yield ($0 \leq Y \leq 1$)

The expression within the brackets represents the theoretical net requirement for electric energy assuming the following reaction:

$$\frac{1}{Y} SiO_2 + \left(\frac{1}{Y} + 1\right) C = Si + \left(\frac{1}{Y} - 1\right) SiO + \left(\frac{1}{Y} - 1\right) CO + 2\,CO \quad (2)$$

and:

- All raw materials entering the furnace have a temperature of 298 K.
- Silicon metal tapped out of the furnace has a temperature of 2000 K.
- Gases out of the furnace as a result of full reduction of SiO_2 have a temperature of 1000 K.
- Gases out of the furnace as a result of partial reduction of SiO_2 have a temperature of 2000 K.

A high value on the silicon yield variable imply that the amount of gas "lost" at the temperature 2000 K is small. The efficiency parameter may be interpreted as a loss parameter defined by the resistance in the furnace electrode system. If R_f represents the electrical resistance between the electrodes and R_e represents the electrical resistance in electrodes and other conductive material the efficiency parameter my be interpreted as:

$$e = \left(1 + \frac{R_e}{R_f}\right) \quad (3)$$

The furnace resistance is usually one of the set point parameter for the furnace control system and will be adjusted depending of furnace conditions. However, for most applications it is assumed to be fixed which implies a constant efficiency parameter.

The economic interpretation of models based on equation (1) with a fixed efficiency parameter is a constant marginal energy loss proportional to energy consumption. Table 1 shows a suggested distribution for the outgoing energy balance for a 75 % FeSi furnace [3]. It is not unlikely that the four

Table 1 : The outgoing heat distribution for a 75 % FeSi furnace [3]

Reduction of Si-elements	30,6 %
Reduction of Fe-elements	3,1 %
Heat loss in tapped FeSi	4,6 %
Heat loss in furnace gases	45,0 %
Heat loss through furnace pot	3,9 %
Heat loss through cooling systems	12,9 %

elements from the top of the list on average are proportional to the amount of produced metal and consumed energy. The two last elements, however, are different. These elements will within the interval of normal production probably not be directly proportional to simultaneous energy consumption. The mass represented by the furnace pot, the electrode system and the raw material in the furnace represent a heat reservoir out balancing short term fluctuations in energy consumption. Even for substantial reductions in energy consumption the total mass within the furnace have a very high temperature compared to the ambient temperature with a corresponding high potential for energy losses. This should imply an energy loss element more stable than elements proportional to energy consumption.

3. ENERGY CONSUMPTION MODELLING

An energy loss element more or less unaffected of the intensity of the melting process implies energy consumption models which in one way or another must be sensitive to the furnace activity level. Theoretical models alone could be based on simple assumptions about the furnace operating level since there are usually no incentives to operate a furnace with reduced load. Practical experiences, however, show that furnace operating level is fluctuating. Models developed for estimating energy consumption and energy losses must therefor include this property.

Before model building it is necessary to define the following set of parameters and variables:

e	-	Energy losses proportional to energy consumption ($e \geq 1$)
q	-	Energy losses with fixed intensity ($q \geq 1$)
Q_{Max}	-	Furnace maximum capacity to reduce SiO_2 [tonne]
E_D	-	Consumed electric energy [MWh]
E_r	-	Required electric energy to reduce SiO_2 without energy losses [MWh]
S_r	-	Amount of reduced silicon [tonne]
S_{FeSi}	-	Amount of silicon in produced FeSi [tonne]
S_{Silica}	-	Amount of silicon in produced silica dust [tonne]
D	-	Operating level ($0 \leq D \leq 1$)
Y_{FeSi}	-	Ordinary silicon yield ($0 \leq Y_{FeSi} \leq 1$)
Y_{Silica}	-	Silicon product ratio ($0 \leq Y_{Silica}$)
H_r	-	Specific energy consumption without energy losses [MWh / tonne]
H_{FeSi}	-	Specific energy consumption based on produced FeSi [MWh / tonne]
H_{Silica}	-	Specific energy consumption based on produced silica dust [MWh / tonne]

The *e* and *q* parameters represent the unknown elements which are to be estimated. The Q_{Max} is assumed to be a parameter with fixed value while the elements following Q_{Max} are all variables. All variables are accumulated values or averages represented by for example averaged 24 hour values.

The model will be built up in two stages. First, the theoretical energy required for loss-free production of standard 75 % FeSi must be calculated. Second, the loss elements will be included in the model. At this stage the operating level elements will also be included. The second stage will also introduce the two alternative versions of the model based on the two silicon yield definitions.

The theoretical specific energy required to produce standard 75 % FeSi[2] without energy losses is calculated to be:

$$H_r = \frac{6{,}11}{Y_{FeSi}} + 0{,}20 \tag{4}$$

Necessary data are found in [4] and [5]. The expression is based on the same assumptions as was applied to calculate equation (1). In addition it is assumed that all ferrous oxides are reduced by CO. The coefficients are slightly different from the coefficients in equation (1) multiplied with 0,75 which is explained by the impurities in standard FeSi.

Before the second stage it is necessary to comment on some of the variables. First, the silicon balance must be defined. Based on an assumption of mass conservation and no loss of silicon the balance between reduced and produced silicon must be:

$$S_r = S_{FeSi} + S_{Silica} = 0{,}4675 \cdot D \cdot Q_{Max} \tag{5}$$

The coefficient 0,4675 refer to the fraction of Si in SiO_2. Equation (5) may also be regarded as a definition of D since Q_{Max} is a constant and the elements on the left side are variables.

The ordinary silicon yield may now be expressed as:

$$Y_{FeSi} = \frac{S_{FeSi}}{S_r} = \frac{S_{FeSi}}{S_{FeSi} + S_{Silica}} = \frac{S_{FeSi}}{0{,}4675 \cdot D \cdot Q_{Max}} \tag{6}$$

The silicon product ratio which not must be mixed with the ordinary silicon yield is as follows:

$$Y_{Silica} = \frac{S_{FeSi}}{S_{Silica}} = \frac{0{,}4675 \cdot D \cdot Q_{Max}}{S_{Silica}} \cdot Y_{FeSi} \tag{7}$$

Since $S_{FeSi} >> S_{Silica}$ the silicon product ratio will be very sensitive to small changes of silicon lost as silica dust.

The industrial definition of specific energy consumption is defined as the ratio of consumed energy divided with produced amount of FeSi. Without energy losses this would be expressed as:

$$H_r = \frac{E_r}{(S_{FeSi} / 0{,}75)} \tag{8}$$

Applying equations (4) and (6) we get:

---

[2]The mass distribution of standard 75 % FeSi is assumed to be 75 % Si, 23,2 % Fe, 1,4 % Al and 0,4 % Ca.

$$E_r = H_r \cdot \frac{S_{FeSi}}{0,75}$$

$$= \frac{6,11}{0,75} \cdot (S_{FeSi} + S_{Silica}) + \frac{0,20}{0,75} \cdot S_{FeSi} \quad (9)$$

The outgoing silicon distribution is defined by the variables S_{FeSi} and S_{Silica}. Equation (9) defines the theoretical energy consumption without energy losses necessary to reduce SiO_2 to Si.

All expressions necessary to model the specific energy consumption with energy losses are now established. The new model will represent a further development of equation (1) since the loss free expression within the brackets in this equation do not include fixed losses insensitive to fluctuations in furnace load. The energy balance which include the energy losses will from now on be defined as:

$$\frac{E_D}{e} = q + E_r \quad (10)$$

The parameter *e* is inspired by the furnace efficiency parameter in equation (1) and may be regarded as the energy losses in electrodes and other conductive material. The parameter *q* may be interpreted as losses additional to losses associated to gases and metal after the electric energy is consumed within the furnace. Based on equation (10) it is now possible to develop two expressions defining how industrially measured silicon yield influence on the specific energy consumption.

The industrial definition of the ordinary specific energy consumption including energy losses is:

$$H_{FeSi} = \frac{E_D}{(S_{FeSi} / 0,75)} \quad (11)$$

Introducing equations (9) and (10) and rearranging give the first version of the model:

$$H_{FeSi} = e\left(\left(6,11 + \frac{0,75\, q}{0,4675 \cdot D \cdot Q_{Max}}\right)\frac{1}{Y_{FeSi}} + 0,20\right) \quad (12)$$

The alternative version will be based on the silica dust production. The ratio of consumed energy to produced silica dust is by some producers used to reveal current furnace condition. The silica dust production is on average regarded as a more reliable indicator of furnace performance than current metal production since silicon dust is never accumulated in the furnace as often happens to metal in cases with tapping problems. The fraction of silicon in silica dust is assumed to be 43,24 %. The definition of the alternative specific energy expression is:

$$H_{Silica} = \frac{E_D}{(S_{Silica} / 0,43)} \quad (13)$$

Introducing (7), (9) and (10) and rearranging give:

$$H_{Silica} = 0,58 \cdot e\left(6,11 + \frac{0,75 \cdot q}{0,4675 \cdot D \cdot Q_{Max}}\right) + 0,58 \cdot e\left(\frac{0,75 \cdot q}{0,4675 \cdot D \cdot Q_{Max}} + 6,31\right) Y_{Silica} \quad (14)$$

Both expressions for H_{FeSi} and H_{Silica} are non-linear and there seems unfortunately not to be any simple transformation which could be applied to produce separable expressions well suited for ordinary regression analysis.

4. ESTIMATING ENERGY LOSS PARAMETERS

The rather complicated structure of equations (12) and (14) imply that estimates for the energy loss parameters must be based on estimates developed especially for these expressions. One alternative is to apply a numerical technique based on the generalised Newton-Raphson iteration method [6]. If $\hat{H}_n$ represent observation no *n* out of *N* then the iteration method can be applied to calculate the parameter values e* and q* which minimise:

$$\Theta = \min \sum_{n=1}^{N} (H_n - \hat{H}_n(e,q))^2 \tag{15}$$

The minimum is defined by the expressions (16) and (17). Based on a set of start values for *e* and *q* each iteration step produce a new set of parameter values which are implemented before next iteration. The iteration procedure continues until the differences between the outcome of two consecutive iterations are less than a set of predefined limits.

$$A(e^*, q^*) = \frac{\partial \Theta}{\partial e} = 0 \tag{16}$$

$$B(e^*, q^*) = \frac{\partial \Theta}{\partial q} = 0 \tag{17}$$

This method do not require any assumptions about the statistical distributions. It is therefore difficult to perform testing on the significance of parameter values. How good the model fit to the collected data may, however, be evaluated as usual:

$$R^2 = \left(1 - \frac{\sum_{n=1}^{N} (H_n - \hat{H}_n(e^*,q^*))^2}{\sum_{n=1}^{N} (H_n - \bar{H}_n)^2} \right) 100\ \% \tag{18}$$

Expression (18) is exactly the same sum of squared residuals as for ordinary linear regression.

5. EMPIRICAL RESULTS

Estimation and evaluation of the energy consumption model will be based on data from 4 full scale furnaces. The data are carefully collected and transformed into averages for periods of 7 or 14 days. Periods missing one or several observations are eliminated. Even periods with furnace load temporarily below 75 % of furnace capacity are eliminated.

Table 2 present data about the furnaces. The furnaces A and B have data about the silica dust production. These furnaces are also almost equal which is confirmed by the negligible difference in Q_{Max}. The Q_{Max} values in Table 2 represent the maximum average found for each furnace. All furnaces except furnace D have 7 days averages. 7 days periods did not produce convergent estimates for furnace D and the period had to be expanded to reduce the effect of temporal furnace instability on the averages. The table also give the 10 and 90 percentiles for the silicon yield observations. These values indicate the relevant interval for the estimated parameters.

Table 2: Furnace data

Furnace	No of periods	Q_{Max} [tonne]	Silicon yield interval 10 %	90 %
A	94	191,2	86,4	94,2
B	86	192,7	86,7	93,2
C	210	113,5	89,4	99,2
D	85	226,9	85,5	92,4

The start values for the iteration procedure was set to $e_0 = 1{,}15$ and $q_0 = 50$ for the three first furnaces. These values did not produce convergent results for the last furnace and the values $e_0 = 1{,}0$ and $q_0 = 300$ started the iteration procedure for furnace D.

Table 3 shows the results from estimation based on equation (12) which represent data on FeSi production. Everyone familiar with statistical analysis with data from full scale furnaces will find the reported R^2 values at high levels which imply a high correlation. The iteration procedure did also converge very fast.

The estimated parameter values for the furnaces A and B are all within the interval of what could be expected. The marginal losses are 13,0 and 18,7 % of the electric consumption while the additional fixed energy loss from the furnace are estimated to be 28,0 and 68,3 MWh pr. day. The estimated parameter values are obviously negatively correlated. This should also be expected from equation (12) since this expression include product terms of *e* and *q*. The results from the two last furnaces, however, are disturbing since the marginal energy losses are less than 1,0 while the fixed losses are very high. Marginal losses less than 1,0 are unlikely and the high values for *q* must, due to the parameter correlation be regarded as the cause or the result of the small *e* values.

Table 3: Results from estimation based on FeSi data

Furnace	FeSi data e*	q*	R^2	No of iterations
A	1,187	27,95	89,00	4
B	1,130	68,33	82,01	5
C	0,966	93,21	85,48	11
D	0,862	337,34	80,85	8

The results from estimation based on the silica dust data are shown in Table 4. The R^2 values are very high and a comparison of the values in Table 3 and 4 shows that furnace A in both cases has the highest R^2 value. The estimated parameter values are far from equal but there are systematic similarities. Furnace A has the

Table 4: Results from estimation based on silica dust data

Furnace	Silica dust data e*	q*	R^2	No of iterations
A	1,114	102,52	98,04	1150
B	1,060	142,46	96,75	2099

highest e^* value while furnace B has the highest q^* value. It is also interesting to observe that the furnace with the smallest R^2 value in both cases has the highest q^* value. This could indicate that fluctuations in specific energy consumption unexplained by the model produce an upward shift for the fixed energy loss estimate.

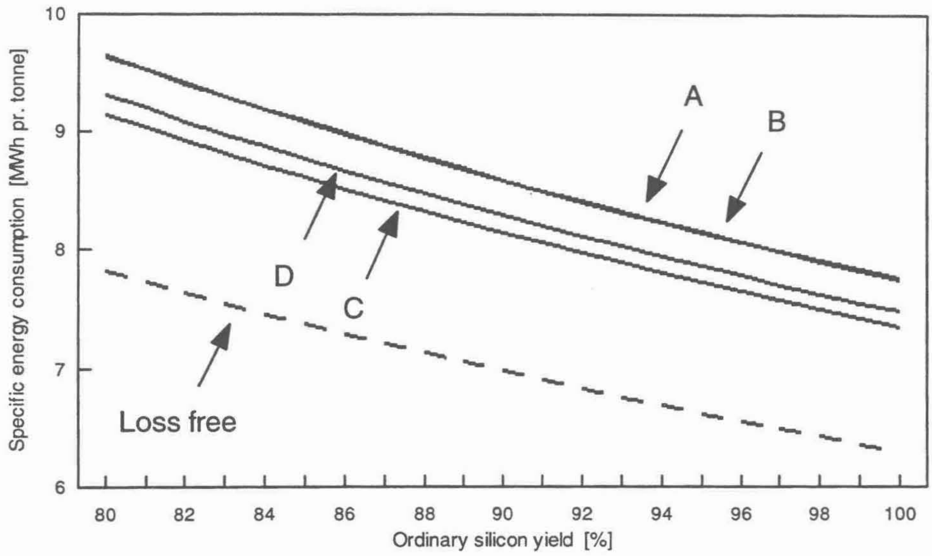

Figure 1: The influence of silicon yield on energy consumption

Figure 1 and 2 show the results from Table 3 implemented in equation (12). Figure 1 shows the sensitivity of specific energy consumption following shifts in silicon yield. The operating level variable D is equal to 1,0 for all furnaces. Furnace A and B are almost equal and despite of the differences in parameter estimates, their curves are overlapping. The next two curves represent furnaces from a different plant and furnace D has a capacity two times the capacity of furnace C. Furnace C has always been regarded as a very efficient furnace and it is not surprising that this furnace should produce a curve closer to the loss free reference curve than furnace D.

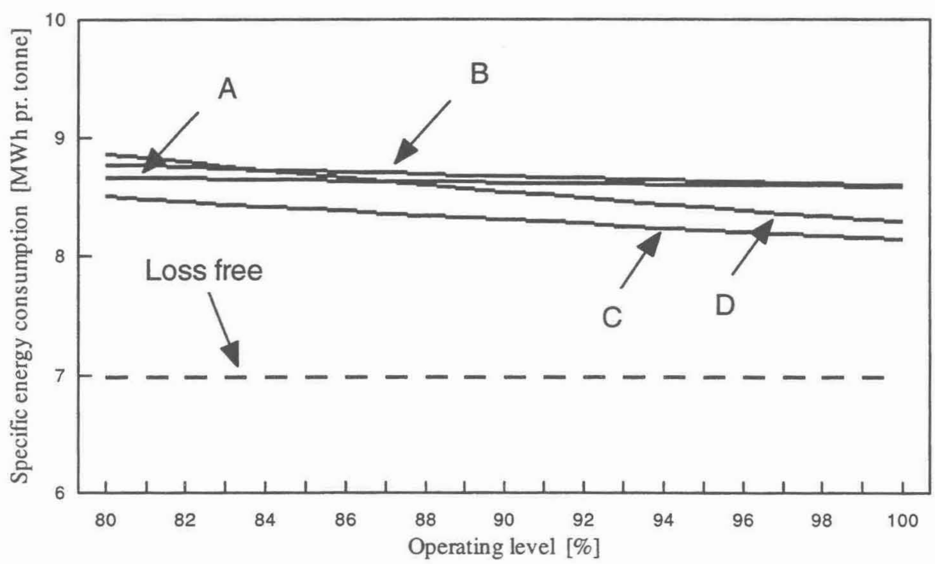

Figure 2: The influence of operating level on energy consumption

Figure 1 shows what could be referred to as the characteristic line for each furnace. For the same silicon yield value the furnaces have a different potential for energy efficiency. The figure shows that the theoretical minimum without energy losses and with a silicon yield equal to 100 % is 6,3 MWh pr. tonne FeSi. Due to the energy losses no furnace in this sample will be able to produce below 7,4 MWh pr. tonne FeSi. Plots are made showing the results in table 4 based on equation (14) implemented in equation (12). These figures show two overlapping curves approximately 0,3 MWh/tonne above the overlapping A and B curves. This difference is still unexplained and will be a subject for further research.

Figure 2 shows the sensitivity of specific energy consumption following shifts in operating level. The ordinary silicon yield is assumed to be 90 % for all furnaces. The loss free curve is horizontal since loss free implies no fixed losses. The slope of the other curves follows the magnitude of the q^* estimate. Furnaces will usually have a higher energy consumption than indicated in figure 2 when they operate on reduced levels. The explanation is that reduced loads or operating levels less than 1,0 usually are a result of operational difficulties. Such data are more or less eliminated due to the selection process.

CONCLUSIONS

The energy consumption models described in this paper which are a further development of Scheis model explains with high R^2 values the relationship between specific energy consumption and silicon yield for 75 % FeSi furnaces. Marginal energy losses and energy losses insensitive to fluctuations in furnace load are estimated to be substantial and both parameters must be included to describe empirical furnace data.

The energy losses also explains important differences between furnaces. Different furnaces which operate with the same silicon yield may have significant differences in specific energy consumption. Out of a sample of 4 furnaces the largest difference is found to be 0,5 MWh pr. tonne.

The energy consumption model also shows the best energy consumption value possible for each furnace. This value is very important in any systematic effort to improve furnace performance and plant profitability.

References:

[1] S. I. Heimdal. Decision support for the production of 75 % FeSi. Dr.ing thesis. Department of Economics at the Norwegian Institute of Technology. 1991. (In Norwegian)

[2] A. Schei. The silicon production process. Elkem Research. Kristiansand 1989. Restricted company material. (In Norwegian)

[3] J. Sandviknes. Energy recovery from dust rich high temperature gases. Kjelforeningen - Norsk Energi. NIF course no 7234 material. 1990. (In Norwegian)

[4] JANAF Thermochemical Tables. Journal of Physical and Chemical Reference Data. Vol 14, supplement no. 1. 1985.

[5] C. Wagner. Thermodynamics of Alloys. Addison - Wesley. Cambridge. 1952.

[6] W. S. Dorn and D. D. McCracken. Numerical Methods with Fortran IV Case Studies. John Wiley & Sons. 1972.