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NEW DEVELOPMENTS OF THE COMPUTER CONTROL SYSTEM FOCS-RF
APPLICATION TO THE HOT STRIP MILL AT SSAB, DOMNARVET
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ABSTRACT

The fuel optimizing control system FOCS-RF has been applied to control the hot strip mill furnace at SSAB, Domnarvet. For this application some new developments of the system were necessary.

The pacing and the slab temperature control had to be coordinated to guarantee slab drop-out temperatures at optimal production rates. The pacing function had to consider both the furnace and the mill capacity and also to control the slab transfers and extractions in full automatic mode.

Moreover, individual slab temperature control had to be developed.

Finally, slab temperature control for hot charged slabs and, in particular, for mixed hot and cold charged slabs had to be developed.
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INTRODUCTION

The FOCS-RF /1/ is a general and unified computer control system for fuel optimization of reheating furnaces. The supervisory system controls the set-points of the control zones based on on-line calculations of slab temperatures and predetermined ideal heating strategies.

The system has now been applied to control a hot strip mill furnace. For this application some new developments of the system were necessary:

- the pacing and the slab temperature control had to be coordinated to guarantee slab drop-out temperatures at optimal production rates

- the pacing function had to consider both the furnace and the mill capacity and also to control the slab transfers and extractions in full automatic mode

- individual slab temperature control had to be developed

- measures had to be taken for stainless steels, which have special requirements regarding surface temperatures

- slab temperature control for hot charged slabs and, in particular, for mixed hot and cold charged slabs had to be developed.

For several years the FOCS-RF system has been the fuel optimizing control system most commonly used by the Scandinavian steel industry. In December 1984, one system for two furnaces in separate mills /2/ was commissioned at SSAB, Domnarvet. During spring 1985, fuel savings of 11-15% have been achieved in one of the mill furnaces (rail mill furnace). Considerable
reductions of oxide scale losses and improvements of steel quality have also been obtained. Based on these positive experiences of the FOCS-RF system it was decided also to apply the system to the hot strip mill furnace at SSAB, Domnarvet. This new system was commissioned in spring 1988.

2 HOT STRIP MILL COMPUTER SYSTEM

2.1 The system today

In the hot strip mill computer system the following functions are implemented:

- rolling schedule managing, as prescribed by the planning system
- furnace temperature control and furnace pacing
- mill pacing
- roughing mill and finishing mills set-up and control
- run-out cooling table set-up and control
- reports, logs and alarms.

These functions are realized in three different computers; A, B and C. Computer A handles the communication with the planning system, furnace set-point control and furnace pacing. Computer B controls the mill pacing, rolling mill set-up, run-out cooling table, weighing-machine and coilers. Computer C is a cold stand-by for both computer A and B.

The PLC (programmable logic control) system and local burner control system of the furnace are ASEA DS8-PP and ASEA DS8-RP system respectively.

Though a total rewamp of the computer system will be done in the end of 1988, the FOCS-RF has been implemented in the old computer configuration at first, in order to get experience before switching to the new computer configuration.
2.2 The system after erection of the new furnace

A new 300 tonne/hr walking beam furnace will be erected beside the old furnace in winter 1988. The new furnace will be running in spring 1989.

This, of course, puts new demands on the computer control system. It has been decided to revamp the computer control system by changing computer A to a MikroVAX 3600 double computer system. At the same time, computer B will be configured as a strict double computer system using the stand-by computer C. This will increase the computer reliability, since today the stand-by computer C has a very complex configuration to be able to serve both computer A, B and I/O interfaces.
For the new furnace, communications to PLC system and local burner control system have to be implemented. Functions for material tracking and communication will be redesigned for the old furnace. Regarding functions for fuel optimization and delay control enhanced FOCS-RF, edition IIIG systems (cf. section 4.6) will be used both for the old and new furnaces. One important thing in those systems is to adjust the furnace pacing to consider both furnace capacities.

3 WALKING BEAM FURNACE AT DOMNARVET HOT STRIP MILL

In the hot strip mill high strength, low alloy, ULC, C-Mn and stainless steel slabs ranging from 110 to 220 mm in thickness and 3 600 to 11 000 mm in length are heated to rolling temperature in a 300 tonne/hr walking beam furnace. The furnace has 9 control zones and 119 burners. The upper and lower preheating zones are equipped with specially developed side burners, which produce an optimum temperature distribution throughout the width of the furnace. Lower heating zones and lower soaking zone have side and front burners respectively. The upper heating zones and upper soaking zone are equipped with radiant roof burners. The upper soaking zone has separate temperature control for the two sides of the furnace. The furnace is fired with heavy oil. The maximum number of full length slabs in the furnace is about 80. The nominal drop-out interval for full length slabs of width 1 250 mm is approximately 5 min. The internal length of the furnace is 37.21 m.

Forward transfer of slabs in the furnace occurs in 1 or 2 rows by means of 10 beams, four movable and six fixed. Beam movements, doors and furnace charging and discharging machines are controlled by the PLC systems. The beams are cooled by a closed evaporative system which circulates a mixture of 95% water and 5% saturated steam. Steam is separated in a drum and fed into the network at a rate of 10-12 tonne/hr at 22 bar.
The extensive heat recovery system in the stacks produces another 10-12 tonne/hr steam. The system is described in /3/.

In the winter of 1986, the furnace was extended 2.21 m at the charging side and a throttling was inserted in the roof in the dark zone of the preheating zone to improve the furnace efficiency.

4 FURNACE SUPERVISORY CONTROL SYSTEM

4.1 Material tracking system

In the furnace computer an advanced function for material tracking, linked to the planning system of SSAB, Domnarvet, is implemented. From this system the following data are obtained for each slab:

- target coiling temperature
- target finishing temperature
- other strip target data
- slab identities
- steel grade
- slab dimensions
- slab weight.

In the furnace area every event, e.g. charging and discharging of slabs, movements of the walking beams, is detected by the system. Based on this information, new positions of the slabs are calculated, the furnace file updated and new data to the FOCS-RF system prepared. FOCS-RF needs these data to calculate new set-points of the control zones temperatures, slab speed and slab temperatures etc.

A smaller tracking file is kept for the area between the furnace and the roughing mill to ensure the correct temperature statistics and adaptation of the heating curves to the measured roughing mill temperatures.
In the mill area the slab positions are detected by means of photocells and from other indicators like sensors for measurement of temperatures, rolling forces and coiling tension.

The extensive tracking system guarantees that the rolling schedule is kept, keeps track of the slabs in the furnace and in the rolling mill.

4.2 Basic system functions

The basic functions make it possible to select different strategies for individual control of the set-points of the control zone temperatures during normal production and a delay in the rolling mill. These strategies are defined below:

MAN - manual heating
NRM - normal rolling mode
ORM - open rolling mode (no temperature feedback control)
MRH - manual reheating
DLY - manual and automatic delay control (MDLY and ADLY mode respectively).

Based on these strategies, the furnace operation schemes below are formed. In Figure 4.1 a functional diagram of the system with feedforward and feedback control blocks is shown. The feedforward control contains a carpet diagram and a delay strategy multiplier table. The carpet diagrams are made up of a number of tables, one for each product, which give the primary optimal control zone temperatures as a function of the speed on steady-state operation. The diagrams are set up from mathematical model calculations and used production practice in the rolling mill. The delay strategy multipliers are used to modify the control zone temperatures during a stop in the rolling mill. The size of the multipliers depends on the time to next rolling.
The dynamics of the process are taken care of by the feedback control. The heating curve of the slabs is calculated, on-line, by the temperature predictor using measured furnace temperatures, fuel flows to the control zones and data from the material tracking system. The difference between the calculated and ideal heating curve gives, via a feedback controller a fine adjustment of the set-points of the control zone temperatures. A detailed description of this basic FOCS-RF system, with edition notation IA, is given in /1/.

Figur 4.1 - Basic functional diagram of the fuel optimizing control system FOCS-RF, edition IA.
4.2.1 Normal production

During normal production, all control zones of the furnace are operated in the normal rolling mode NRM. The feedback control of the system is active and the slabs are heated according to the specified ideal heating curves. These curves are stored in the furnace specific data base for the different products as a function of the drop-out interval (speed). The open rolling mode ORM, (no temperature feedback control), is used when starting up the production after e.g. a longer down time. The manual reheating mode MRH has only been used for short periods of time, when filling the furnace with slabs.

The system has 30 different products and 25 different ideal heating curves with the possibility of increasing those numbers to 50 and 60 respectively. Products are formed for every combination of steel grade, group of slab thickness and group of target drop-out temperature.

4.2.2 Unplanned stops

During a short stop in the rolling mill the automatic delay control ADLY is activated and the set-points of the control zones are automatically turned-down. When a slab is discharged from the furnace the set-points of the control zones are turned-up to the values stored in the carpet diagrams, according to exponential curves. The delay strategy multipliers are selected so that the slabs in the soaking zone are ready for extraction at any time.

To further turn-down the furnace the operator must activate the manual delay control MDLY and enter an estimation of the time to next rolling (cf. section 4.2.3).
4.2.3 Planned stops

During a stop of known length, caused by e.g. a roll change or a rolling mill adjustment, the operator activates the manual delay control MDLY and enters the time to next rolling. The turn-downs of all the furnace zones are then performed according to exponential curves to certain temperatures determined by the current product(s), drop-out interval (speed) and given time to next rolling. When the time for turn-down control has elapsed, the furnace is turned-up according to the strategy(ies) prescribed in the carpet diagram(s) and the last multiplier table. The slabs are not immediately ready for extraction during the manual delay control.

Moreover, the feedback is also applied during unplanned and planned stops, ensuring correct drop-out temperatures.

The system contains a total of 16 different tables for the delay strategy multipliers.

4.2.4 Programmed start-up and turn-down control

A special strategy is included to account for very long stops such as weekend start-ups or turn-downs and stop shifts. The operator specifies zone-wise the holding or operating temperature and the heating time. The set-point of each control zone is then changed between the holding and operating temperature or vice versa according to an exponential curve.

4.3 Pacing

The pacing function controls the drop-out interval (speed) considering the production capacity of the rolling mill and furnace(s). The rolling mill capacity is obtained from the mill pacing of the supervisory control system for the rolling
mill in terms of the minimum possible drop-out interval. The largest of the drop-out intervals of the furnace(s) and mill pacing is selected as the drop-out interval of the whole process.

Because a negative deviation between the calculated and ideal heating curve reflects a lack of heating capacity in a control zone, a pacing strategy can be formed by defining the largest acceptable temperature shortage for each control zone.

During normal pacing, the drop-out interval (speed) of the furnace(s) is determined from the largest acceptable temperature shortage in the different control zones of the furnace, specified in one for each product selectable table. For cold charged slabs the temperature shortage is obtained from a weighed difference between the calculated and ideal heat contents over the length of the considered control zone. In the hot charging case an additional weighing procedure is included in the calculation of the temperature shortage to take the colder slabs more into account. The weighing procedure can be tuned so that only the coldest slab in each control zone is considered.

Provided that the rolling mill is not the bottle neck, the drop-out interval (speed) is controlled by means of speed in-/decrements. By incrementing the furnace speed until one zone reaches its limit value for the temperature shortage, the limiting control zone is found. This control zone will be the controlling control zone until the temperature shortage of another control zone will exceed its limit value more than the controlling control zone does. When the absolute value of temperature shortage for the controlling control zone comes close to its limit value the size of the in-/decrements is reduced to give a stable settling procedure. The furnace will be running at its maximum capacity. The size of the accumulated in-/decrements is limited.
Reduction of speed is obtained in the following cases:

- too high waste gas temperature
- too high control zone temperatures
- too high temperature gradients (calculated using finite-difference temperature model)
- too high surface temperatures (calcualted using finite-difference temperature model).

The maximum permitted temperature gradients of the slabs are specified for the upper control zones of the furnace in one for each product selectable table. Analogously the maximum permitted surface temperatures of the slabs are specified for the upper and lower control zones of the furnace in another for each product selectable table. These two tables are defined to meet the quality demands for each steel grade. Cross reference tables are used to link the products and the above three tables together. For each product the maximum throughput of the furnace can be specified.

The operator can fix or put an upper limit on the throughput, fix or put a lower limit on the drop-out interval and manually increase or decrease the calculated speed by a percentage value.

The table specifying the maximum permitted temperature shortage in the different control zones of the furnace can be adjusted with respect to the future furnace capacity in two different ways.

Case 1: When slabs belonging to the next rolling lot fill up a control zone, the acceptable temperature shortage in the control zone should be increased by a certain factor, e.g. 100%. For each slab a label, recognized by the FOCS-RF system, is used by the material tracking system to mark this.
Case 2: For control zones containing slabs being discharged after a roll check or another planned stop, the maximum permitted temperature shortage is increased by a certain number of degrees centigrade per each minute planned stop, e.g. 5°C per minute stop. The operator indicates where in the lot the stop will occur.

The start-up drop-out interval (speed) after a stop is calculated from the maximum furnace throughput for the slabs, next to the discharge door, in the soaking zone. A mean drop-out interval is calculated for the first slabs in turn for extraction. The same holds when the rolling mill has been the bottle-neck. The actual furnace capacity is recalculated each time the walking beams have completed their cycle and the temperature predictor has calculated new temperatures for both beams.

4.4 Individual slab temperature control

The ideal heating curves are essential for the feedback control and for the pacing function. Each product has a set of ideal heating curves related to the drop-out interval (speed) of the slabs.

In earlier revisions of the FOCS-RF system the ideal heating curves were expressed in degrees centigrade. Hence, each curve was directly linked to a target drop-out temperature. This will cause no problem in rolling mills, where the number of products and target drop-out temperatures are small and where the stocks are rolled in lots.

In a hot strip mill, however, this is not the case. Therefore, the ideal heating curve is now given as permillage values of the target drop-out temperature for each length position. The actual value of the temperature of the ideal heating curve is obtained by multiplying the target drop-out temperature for a certain slab with the permillage value of the ideal heating curve for the actual slab position. In this way
one ideal heating curve can now suit a range of target drop-out temperatures.

4.5 Target temperature calculations

The target finishing and coiling temperatures are determined from the quality requirements and are given from the planning system for each slab upon its charging into the furnace.

From the finishing mill practice and the target strip thickness, thickness and temperature of the transfer bar are determined, optimizing towards the greatest possible thickness and coldest possible transfer bar.

Now the target slab drop-out temperature can be determined from the rougher pass schedule, holding time before the last pass etc. using backwards calculations. These target temperature calculations are illustrated in Figure 4.2.

This procedure will give individual slab target temperatures, which are not always possible to achieve due to physical limitations in the furnace. Heating of slabs with different sizes and/or temperature requirements, positioned close together, will always be a compromise.

4.6 Adaptation of the ideal heating curve

In the rolling mill, the surface temperature of the transfer bar is measured after the last pass in the rougher. This temperature is used for finishing mill set-up and for adaptation of the ideal heating curve.

The used rougher practice can differ from the one assumed, when the rougher temperature model calculates the furnace target drop-out temperature from the target finishing temperature.
Therefore, the model is also used to calculate a revised rougher target temperature from the actual used practice and the actual drop-out temperature calculated by the temperature predictor. This gives a good measure of a temperature error at the rougher, since adjustment is made for the actual used practice. These above two set-up temperature calculations are also illustrated in Figure 4.2.

In the present system, the revised rougher target temperature is compared with the measured rougher temperature after the last pass. If the deviation between these two temperatures is greater than a certain limit value, one adjustment of the temperature in each position of the ideal heating curve is made. Typical values are 0.01-0.1°C, if the deviation is greater than 5-15°C. The sizes of the accumulated adjustments to the ideal heating curve are limited. An illustration of the adaptation of the ideal heating curve is given in Figure 4.3.

The adaptation function is not activated until the system has been operating in the normal rolling mode NRM for a certain period of time. This function is automatically deactivated a period of time, if the pyrometers in the roughing mill have a malfunction, a product change has occurred, or if a change to another mode than the normal rolling mode NRM is made. Provided that the adaptation function has been deactivated the above period of time must elapse before the function is activated again.

This function can optionally be included in the basic FOCS-RF system.

4.7 Other special functions of the FOCS-RF system

In FOCS-RF, edition IIB the temperatures can be calculated in, e.g. 5 points along a vertical centre line through the slab, using finite differences. This is used when a more accurate calculation or control of the surface to surface temperature
TFET = Target furnace exit temperature
FET = Furnace exit temperature (calculated by FOCS-RF)
TRT = Target rougher temperature
RT = Measured rougher temperature
RTRT = Revised target rougher temperature
TFT = Target finishing temperature
FT = Measured finishing temperature
TCT = Target coiling temperature

Notations: 
- : Target temperature calculations
- - : Set-up temperature calculations

Figure 4.2 - Target and set-up temperature calculations in the hot strip mill at SSAB, Domnarvet.
In the FOCS-RF, edition IIC on-line oxide scale loss calculations are included. The used mathematical model /4/ can describe a combination of linear and parabolic scale growth.

Linear scale growth occurs by diffusion of oxygen through the atmosphere boundary layer surrounding the slab and the oxidation with CO\textsubscript{2} and H\textsubscript{2}O. The parabolic scale growth occurs by diffusion of Fe\textsuperscript{2+} iron ions through the growing wüüstite layer in the scale. In the furnace specific data base oxide scale growth data are stored for 8 different steels heated in 2 different furnace atmospheres. The amount of scale formed on each slab is shown in the furnace map.

Figure 4.3 - Illustration of the adaptation of the ideal heating curve used in the FOCS-RF system.

gradients is required. It can help to control the bendings during rolling in the rougher.
From the program editions IIA, IIB and IIC, the following editions can be created IID=I+II, IIE=I+III, IIIF=II+IIF and IIG=II+IG.

For hot charging FOCS-RF editions IIIA, IIIB, ..., IIG have been developed with notations analogous to the ones for editions IIA, IIB, ..., IIG.

The FOCS-RF MINI system only includes the feedforward part of the FOCS-RF system, (no temperature calculations), in Figure 4.1.

An illustration of the different FOCS-RF editions is given in Figure 4.4.

Figure 4.4 - Illustration of the different editions of the FOCS-RF system.
4.8 Reports and logs

A computer control system gives an excellent opportunity to log different types of data in order to follow up the furnace and mill performance. Below, some of the furnace reports are briefly described.

The shift report contains information about the number of extracted slabs, extracted tonnes and extracted tonnes per effective time, total and specific oil consumption (litre/tonne), oil consumption during effective time (litre/tonne effective time), numbers and lengths of stops etc. on an hourly basis. The shift reports are saved for five weeks in the system. The weekly production report is an assembly of the shift reports on a weekly basis.

In the rolling mill, the slab temperature is measured with a radiation pyrometer after the last pass in the rougher. A log over the temperature performance of a campaign of slabs is printed at the end of each campaign. A campaign is rolled between a shift of rolls during approximately 8 hours.

In order to evaluate the performance of the system, statistic logs over drop-out temperatures, deviations from target drop-out temperatures, rougher rolling temperatures and deviations from target rougher rolling temperatures are accumulated over the week. The logs show number of logged slabs, mean value and standard deviation of the above temperatures divided into product number, speed interval group and mode of system operation. Moreover, the first 10 slabs extracted after a delay are separated from the others, which gives an opportunity to tune the delay strategy multipliers for the soaking zone during a delay in the rolling mill. These statistics are accumulated over the ongoing year.

This log provides a nice instrument for tuning, since a change in almost all parts of the system can be traced here.
In the MikroVAX system, a slab log is planned for the calculated slab temperatures, the surrounding wall and gas temperatures at all slab positions in the furnace. This log is called a slab heating certificate log.

In the future, additional logs will be included in the system.

5 EVALUATION OF THE COMPLEX HEATING MODEL IN STEELTEMP

5.1 General

Before a new FOCS-RF system can be commissioned, the carpet diagrams and delay strategy multiplier tables have to be set up. This can either be done from earlier experiences or by simulating the furnace using off-line mathematical models.

In this particular case there were previous experience to use, but nevertheless it has been preferable to run the off-line furnace models in STEELTEMP /5/. For this reason, the complex heating model in STEELTEMP has been evaluated.

5.2 Experiment

Before the test slab was charged into the furnace, the production had been running at normal rate for 4 hours. The test slab was a 220x1250x5400 mm slab charged in a double row. During the trial, no disturbances in the production occurred. Oxygen enrichment of the combustion air was used in the upper and lower preheating zone. The residence time of the test slab in the furnace was 2 h 21 min.

The test slab was supplied with trailing thermocouples, applied from the top to 30, 110 and 190 mm depth, nailed to the slab and connected to a temperature recording EFH-sonde /6/, stored in an isolated box with a water reservoir and water vapour outlet. The box was fastened to the test slab and followed with it through the furnace.
The test conditions are summarized below:

Test slab: 220x1250x5400 mm, type SIS 1265
Mean slab: 220x1250x10686 mm
Mean gap between slabs: 79 mm
Initial slab temperature: 10°C
Fuel: Heavy oil Eo5 (1.0 weight% S)
Furnace filling: 28 mean slabs
Number of slabs in the furnace zones: 3.43 5.00 3.45 2.10 5.71 0.49
Mean drop-out interval: 5 min 02 s
Control zone temperatures: 1300, 1330, 1350, 1310°C
1310, 1310, 1340, 1280°C.

The furnace temperature was almost constant during the experiment. In Table 5.1 the wall/roof temperatures and waste gas temperature recorded during the trial are shown.

Table 5.1 - Wall/roof temperatures and waste gas temperature recorded during the trial (No. 2).

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top zone</td>
<td>Bottom zone</td>
</tr>
<tr>
<td>TE1</td>
<td></td>
</tr>
<tr>
<td>TE2</td>
<td></td>
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<td>TE3</td>
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<td>TE14</td>
<td></td>
</tr>
<tr>
<td>TE15</td>
<td></td>
</tr>
</tbody>
</table>

Waste gas temperature TEO: 860°C
During the experiment, the fuel flows and the combustion air flows to the control zones varied considerably. The values used in the STEELTEMP calculations are the mean values of the recorded flows for the trial. In Table 5.2 the fuel flows, the fuel temperatures, the combustion air flows, the combustion air temperatures, the oxygen gas flows and oxygen enrichments are put together for the experiment.

Table 5.2 - Mean values of fuel flows, fuel temperatures, combustion air flows, combustion air temperatures, oxygen gas flows and oxygen enrichments to the control zones for the trial (No. 2).

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<tbody>
<tr>
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<td>2 017</td>
<td>120</td>
<td>28 144</td>
<td>461</td>
<td>1 083</td>
<td>24.0</td>
</tr>
<tr>
<td>2</td>
<td>1 280</td>
<td>120</td>
<td>15 828</td>
<td>496</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>672</td>
<td>120</td>
<td>8 304</td>
<td>496</td>
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<td>--</td>
</tr>
<tr>
<td>4</td>
<td>240</td>
<td>120</td>
<td>3 018</td>
<td>434</td>
<td>--</td>
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</tr>
<tr>
<td>5</td>
<td>2 406</td>
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<td>31 495</td>
<td>461</td>
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<td>120</td>
<td>10 848</td>
<td>496</td>
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</tr>
<tr>
<td>8</td>
<td>351</td>
<td>120</td>
<td>4 207</td>
<td>434</td>
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</tr>
</tbody>
</table>

During the experiment, the gas temperatures were recorded with suction pyrometers inserted in the furnace through the roof. These pyrometers were of two different types, one manufactured by Land (Cr/Al-thermocouple up to 1100°C) and the other two by International Flame Research Foundation IFRF (Pt-thermocouples up to 1600°C). The recorded gas temperatures are given in Table 5.3 for the trial.

The net calorific value and the mean specific heat of the heavy oil are:

\[ H_f = 41 000 \text{ kJ/kg} \]
\[ c_{pf} = 1 840 \text{ J/kg°C}. \]
Table 5.3 - Used suction pyrometers, their height above the hearth and the recorded gas temperatures for the trial (No. 2).

<table>
<thead>
<tr>
<th>Measuring point</th>
<th>Type of suction pyrometer</th>
<th>The distance of the pyrometer to the hearth [mm]</th>
<th>Gas temperature [°C]</th>
<th>Distance from the charge door [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TG1</td>
<td>Land</td>
<td>700</td>
<td>1050</td>
<td>5800</td>
</tr>
<tr>
<td>TG2</td>
<td>IFRF</td>
<td>700</td>
<td>1250</td>
<td>10050</td>
</tr>
<tr>
<td>TG3</td>
<td>IFRF</td>
<td>700</td>
<td>1440</td>
<td>22200</td>
</tr>
</tbody>
</table>

From the oil analysis, the fuel/air ratios, the air preheat temperatures and the oxygen enrichments of the control zones, the flue gas compositions are calculated for the control zones. The results are given in Table 5.4.

Table 5.4 - The calculated flue gas compositions of the control zones for the trial (No. 2).

<table>
<thead>
<tr>
<th>Control zone</th>
<th>CO₂</th>
<th>H₂O</th>
<th>SO₂</th>
<th>O₂</th>
<th>N₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 and 5</td>
<td>10.6</td>
<td>10.0</td>
<td>0.0</td>
<td>5.1</td>
<td>74.3</td>
</tr>
<tr>
<td>The remaining</td>
<td>10.1</td>
<td>10.2</td>
<td>0.0</td>
<td>3.1</td>
<td>76.6</td>
</tr>
</tbody>
</table>

The beams are cooled by a closed evaporative system, which produces steam at a rate of 12 tonne/hr. From gained experience it is known that the heat flow rate losses to the beams in the dark and burner zones are 150 and 300 kW/m respectively. Because the slabs cover the beams, it is assumed that 10% of the losses can be assigned to the top zones and 90% to the bottom zones.

To the zones additional heat flow rate losses have been added corresponding to other heat losses through broken walls and roof, estimated to 20 and 40% of the beam losses for the dark and burner zones respectively. In the STEELTEMP calculations it is assumed that the furnace linings are unbroken and in
best conditions, which is seldom the case in practice. The used values for the heat flow rate losses to the beams in the dark and burner zones are 180 and 420 kW/m respectively.

5.3 Furnace instrumentation and modelling

In the mathematical model of the furnace the upper and lower preheating zones are each divided into two dark zones and two burner zones, zones 1-4 and 11-14 respectively. The two upper and lower heating zones correspond each to three and four burner zones, zones 5-7 and 15-18 respectively. The upper soaking zone is divided into three burner zones, zones 8-10. The lower soaking zone consists of one burner zone, zone 19. The wall/roof temperatures are measured with conventional thermocouples in all zones. In dark zone 1 the gas temperature is measured with a conventional thermocouple in the waste gas flue. The furnace instrumentation and modelling are shown in the side view of the furnace in Figure 5.1.

In the STEELTEMP calculations the zone boundaries for the top and bottom zones must coincide. For the hot strip mill furnace this implies that two fictitious slave burner zones, zones 6 and 8 must be introduced in the upper part of the furnace. Analogously, two fictitious slave burner zones, zones 16 and 18 must be introduced in the lower part of the furnace.

The gas temperatures are assumed to vary, corresponding to plug flow, in all zones. In the calculations the heat transfer by forced convection between the gas and the top surface of the slab is accounted for in dark zone 1. The characteristic length of the slab has been chosen equal to the slab width 1.25 m and the flow velocity of the gas to 10 m/s in the forced convection model. This value of the flow velocity of the gas has also been used in the oxide scale growth calculations.

The emissivities of the slab and walls/roof are assumed to be
\( \varepsilon_s = 0.8 \) and \( \varepsilon_w = 0.75 \) respectively.

A certain air infiltration occurs through the charge door, \( (\eta_1 = 1.005 \text{ and } \eta_{10} = 1.008) \), and the discharge door, \( (\eta_{11} = 1.005 \text{ and } \eta_{19} = 1.008) \), despite the fact that over-pressure prevails in the furnace.

**Figure 5.1** - Instrumentation and modelling of the walking beam furnace of the hot strip mill at SSAB, Domnarvet.
5.4 Results and heat balance of the furnace

In the complex heating model the heating curve of the slabs, the gas and wall/roof temperatures in the furnace are calculated from the geometrical and thermal description of the furnace, fuel and air flows, fuel and air temperatures to the control zones etc.

In Figure 5.2 the results of the calculations are shown. The upper part of this figure shows the calculated gas and wall/roof temperatures together with the measured slab temperatures 30, 110 and 190 mm below the top surface. From the figure it can be seen that the calculated gas temperatures are in good agreement with the gas temperatures measured with the suction pyrometers. Moreover, the gas temperature measured with a conventional thermocouple in the waste gas flue also agrees well with the corresponding calculated temperature.

Most of the calculated wall/roof temperatures agree well with the temperatures measured with conventional thermocouples. Excluded are the thermocouple in the 1st (5th) control zone, where the thermocouples in the burner zones and the lower first dark zone record 60-150°C higher temperature than the calculated ones. It is not trivial to explain the deviations. One possible explanation may be that the large fuel input, combined with the side burner firing, creates a different gas flow in this part of the furnace.

The throttling in dark zone 1 results in a higher temperature being recorded in the bottom of dark zone 11 than in the corresponding position in the roof in dark zone 1. The hot furnace gases are forced down in the lower part of the furnace avoiding creation of cold air regions.

From the lower part of Figure 5.2 it can be seen that the calculated bottom surface and center temperatures are in good agreement with the temperatures measured, (maximum error 40°C), in the corresponding positions in the test slab.
Figure 5.2 - Calculated and measured temperatures when heating 220x1250 mm C-Mn steel to 1250°C in the walking beam furnace of the hot strip mill at SSAB, Domnarvet (trial No. 2).
From the complex heating model, a total heat flow rate balance for the furnace can be obtained. This balance is shown in Figure 5.3. From this figure it can be seen that the furnace efficiency (ratio between heat to steel and heat supplied with the fuel) is 60%. In the recuperator, 44% of the heat flow rate in the waste gases is recovered, corresponding to a combustion air preheat temperature of approximately 475°C. The beam losses are 10% of the total heat flow rate supplied to the furnace. It can also be seen that only 3% of the total heat input is transmission losses through unbroken walls. In the calculations, additional transmission losses of 3% have been included in the beam losses. Finally, the heat of oxidation corresponds to 1% of the total heat input.

Figure 5.3 - Total heat flow rate balance (MW) for the walking beam furnace of the hot strip mill at SSAB, Domnarvet (trial No. 2).
6 RESULTS

Results from the FOCS-RF implementation in the hot strip mill will not be available prior to the SCANHEATING II conference in June 1988.

7 REFERENCES


