A Control System for Fuel Optimization of Reheating Furnaces

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A general and unified computer control system for fuel optimization of reheating furnaces has been developed. The system contains functions for material tracking, fuel optimization and delay control, programmed start-up and turn-down control, operator communication, logging and alarm. The fuel optimization and delay control strategy consists of carpet diagrams (tables of primary optimal control zone temperatures) and delay strategy multipliers. The delay strategy multipliers automatically modify the control zone temperatures when a stop occurs in the rolling mill. The magnitude of the multipliers depends on the time to next rolling.

The heating curve of the stocks is calculated on-line using measured furnace temperatures, fuel flows to the control zones and data from the material tracking system. In the mathematical model new furnace temperatures can easily be added, new dark and burner zones inserted and different zone temperature profiles and heating conditions accounted for. 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.

The system has been used to successfully control 1 pusher furnace, 3 walking beam furnaces and 1 rotary hearth furnace in the Scandinavian steel industry during several years.

Introduction

In the nineteen-sixties and seventies a number of computer control systems were developed in Europe to optimize hot strip mill performance. One of the first system was developed in connection with the planning of Hoogovens' 88-in. hot strip mill [1] and [2], which was commissioned in 1969. In this system the slab temperature is measured with a total radiation pyrometer in each control zone. The fuel flow is then controlled such that the target and measured pyrometer signal agree. When substantial differences between the target and measured slab surface temperature in the roughing mill occur, it is possible to change the pyrometer signal settings for each control zone by a correction factor. In order to avoid fluctuations in the fuel flow at each push the system has later been upgraded with direct fuel flow control [3].

During a stop in the rolling mill the settings of the pyrometer signals are turned-down to avoid overheating the slabs and save fuel. When production is restarted the settings are automatically turned-up. The relationships between on one hand the pyrometer settings and on the other hand slab data, push rate, strip finishing data and rolling mill schedules are obtained by off-line mathematical model calculations.

Within the British Steel Corporation (BSC) [4], in collaboration with Lackenby Works, another computer control system was developed in the seventies. The control actions, necessary to produce the optimum heating of the slabs, are derived from a combined feedforward and feedback control strategy in this system. The feedback control strategy provides zone temperature set-points and push rate from slab and production data on steady-state operation. The feedback control is derived from measurements of the thermal state of the slab and compensates for inaccuracies in the feedforward control by modifying the set-points and push rate.

From the beginning a proximity sensor [5], located just beneath the slab, imbedded in the ceramics surrounding the skid pipes, was used to measure the slab temperature. Since the use of this sensor was associated with considerable maintenance problem BSC developed in the late seventies a new method [6] for calculating the slab temperature from the furnace temperatures measured with thermocouples located in the walls and roof.

In the late seventies another computer control system was developed within Betriebsforschungsinstitut (BFI) [7]. In this system an observer is used to calculate the slab temperature from the measured fuel and combustion air flow to each control zone. The control zones are divided into dark and burner zones in the mathematical model of the furnace. A predictor then determines the optimal setting of the fuel flow to each control zone, on-line, such that the energy consumption within the furnace will be minimum. The observer has been evaluated for a 3-zone pusher furnace against a measured heating curve.

Models of continuous reheating furnaces with application to automatic control have been worked out within Institut de Recherches de la Sidérurgie Française (IRSID) [8] in the late seventies and early eighties. These models consist of a reheating model, a fuel consumption model and a model characterizing the quality of reheating with respect...
to oxide scale losses, decarburization and skid marks. IRSID placed its models and experience to USINOR’s disposal in order to develop a computer control system for the reheating furnaces of the hot strip mill at Dunkerque. The system was put into operation during the autumn 1982.

In this paper a general and unified computer control system for reheating furnaces is presented. The system has a modern structure with feedforward and feedback control blocks. The feedforward control block consists of carpet diagrams and delay strategy multipliers. The former gives the primary optimal control zone temperatures as a function of the drop-out interval. The delay strategy multipliers are used to modify the control zone temperatures during a stop in the rolling mill.

In the mathematical model used to calculate the heating curve of the stocks the furnace is divided into dark and burner zones containing one and only one real or fictive thermocouple measuring point for gas and wall or roof temperature respectively. Different heating conditions and furnace temperature profiles can be accounted for in each zone. The difference between the calculated and ideal heating curve is fed to the feedback control block and gives a fine adjustment of the control zone temperature setpoints.

There are a considerable number of smaller furnaces which could benefit from a fuel optimizing control system but which do not justify a large capital outlay. A special purpose micro-computer unit containing in principle a stock list, the feedforward control block, shift reports, weekly production reports and stop time logs has therefore been developed. This system will be possible to upgrade to a comprehensive system including heating curve calculations and feedback control.

Since August 1982 the system has been used to successfully control the 100 ton/hr top-fired walking beam furnace of roughing mill No. 2 at Swedish Steel AB, Luleå. One system for rotary hearth No. 30 of pipe work No. 4 at SKF Steel, Hofors was installed in August 1983. Another system for the top- and bottom-fired double walking beam furnace of the heavy plate mill at Avesta was commissioned in September 1984. In this application the advanced furnace computer control system is linked to the rolling mill computer. The system and achieved fuel savings are described in [9]. In the latest installation one computer is used to control two furnaces in separate mills. These furnaces are the walking beam furnace of the rail mill and the pusher furnace of the wire rod mill at Swedish Steel AB, Borlänge. These installations fully prove the flexibility of the FOCS-RF software package.

The program MVDMTS transfers charge number, stock identities, beam in furnace, stock pitch, stock dimensions and product number between the material tracking system and the database DB.

The process interface PROVAL consists of a number of programs, which transfer measured process values, setpoints and digital signals between the system and the local burner control system, the position and sequence control system. In the interface functions for logging and alarm treatment are also included. The interface contains a number of operator commands to communicate with the different functions.

The communication between the process interface PROVAL and the furnace specific data base DB is handled by the interface program DBPV.

Using the operator communication DBOP charging table maps, furnace maps and situation maps can be shown on the operator’s video display unit (VDU), parameters and table values can be changed and shift reports, weekly production reports and stop time logs etc. printed out on the logging terminals. Moreover, different strategies for fuel optimization and delay control and programmed start-up and turn-down control can be activated.

### Material tracking system

From the material tracking system information about charge number, stock identities, beam in furnace, stock pitch, stock dimensions and product number is obtained. This information is necessary for presenting the positions of stocks in the furnace, calculation of the heating curve, setting up shift reports, weekly production reports and stop time logs etc. In plants with large ordinary steel productions there are normally central material tracking systems in the rolling mills. In such cases the necessary information can be transferred to the furnace computer control system using a data link from the material tracking system. In other cases a simple function for material tracking based on a stock list can be implemented in the furnace computer.
In the material tracking system the stocks can either be defined on an individual basis, in the order they should be rolled, or on a lot basis. The principle set ups of input data of the material tracking system in the two cases are shown below.

**A**  
- The stocks are defined on an individual basis  
- rolling parameters  
- charge number  
- stock identities  
- stock dimensions  
- steel grade  
- stock dimensions

**B**  
- The stocks are defined on a lot basis  
- rolling lot and lot size  
- charge number  
- stock identities  
- beam in furnace  
- product number  
- stock dimensions

With a rolling lot it is referred to stocks of the same dimensions and steel grade, possibly from different charges, which are rolled to the same final product. Stocks of the same dimensions and steel grade heated to the same temperature form one product.

In both cases the product number can be determined from other data in the material tracking system using look-up tables. For instance the product number might be determined from the rolling parameters, the steel grade and the stock dimensions.

Before the stocks are charged into the furnace a more or less rigorous identity control against certain data in the material tracking system is performed. Stocks, which are not identified correctly, are removed from the furnace and the system. The material tracking system reduces the risk for mixing up the stocks, which leads to reduced material losses.

A number of rolling lots can be defined in advance in the system. In a charging table map, e.g. the number of stocks, remaining in the rolling lot. This will give the operator a possibility to check that the lot contains the specified number of stocks. Possibilities to simple change in the stock list are at hand.

Different rolling lots are separated by a lot gap consisting of a number of empty positions. When changing between two lots containing stocks of essentially different dimensions or steel grades a larger lot gap is used. The size of the lot gap can be determined from the product number of the stocks in the rolling lot before and after the lot gap using look-up tables. The system should automatically make the lot gap.

A number of empty positions in the leading gap before the rolling lot can be labelled as fictive products. The carpet diagram temperatures of the fictive product can be selected so that they corresponds to the demand of extra heat input required by the new product. In order to avoid overheating the steel the delay strategy multipliers corresponding to the fictive product are selected such that a quick turn-down of the control zone temperature is obtained during a stop in the rolling mill.

**Fuel optimization and delay control**

**General description**

The system consists of a feedforward and feedback control block shown in Fig. 2. The feedforward control block contains a carpet diagram and delay strategy multipliers. 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 drop-out interval on steady-state operation. The diagrams are set up from construction drawings of the furnace, 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. They are stored in tables analogous to the carpet diagrams.

In each control zone there is a critical point. A product change, i.e. a change of the controlling product of the control zone, occurs when a new product passes the critical point. The center of the product is used as reference point.

In the lot gap between slabs of essentially different thicknesses a fictive product can be introduced. A product change occurs when the center point of the fictive product passes the critical point. The set-point is then changed to the value valid for the product following the fictive product. This technique is used to obtain a change of the set-point to the value required by the new product. No temperature calculations are made for the fictive products.

The temperature predictor calculates the heating curve of the stocks from measured values of the furnace temperatures, fuel flows to the control zones and data from the material tracking system. In the temperature predictor new measuring points for gas and wall or roof temperatures can be introduced and the occurrence of dark and burner zones, different zone temperature profiles and heating conditions accounted for. The difference between the calculated and ideal heat content is fed to a feedback control block, which gives a fine adjustment of the set-points of the control zone temperatures.

A furnace map shows stock data, the position, the residence time and the temperatures of the stocks in the furnace on the operator’s VDU. The difference between the
calculated and ideal heating curve is visualized graphically in a situation map. Shift reports, weekly production reports, stop times logs and energy distribution logs can be printed out on logging terminals. Moreover, parameters and table values can be changed using the operator communication.

**Functional description**

The function makes it possible to select between different strategies for individual control of the set-points of the control zone temperatures during normal production and a stop in the rolling mill. The strategies are defined below

**MAN** – manual heating  
**NRM** – normal rolling mode  
**ORM** – open rolling mode (no temperature feedback)  
**MRH** – manual reheating  
**DLY** – manual and automatic delay control

In the normal rolling mode NRM the switching on and off of the temperature feedback is controlled by the temperature difference between the set-point and process value of the considered burner controller. By using different limit values for the temperature difference, when switching on and off, a hysteresis function is obtained.

The temperature feedback can also be switched off zone-wise by putting the zone status to ORM. This is used when starting up the production after e.g. a weekend stop, stop shifts or when the feedforward control block is tested out. The switching on and off of the temperature feedback occurs bumbleless. The working range of the temperature feedback signals is limited.

If the operator finds that the stocks during a stop in the rolling mill do not become warm enough he/she can activate the manual reheating MRH, which turns-up the set-points of the pointed out control zone temperatures to the primary values given in the carpet diagram for the current drop-out interval (constant multipliers are set to 1) during a certain prescribed period of time. The turn-up control follows an exponential curve. The function is also used for testing out the product change.

When the time to extraction of next stock exceeds the drop-out interval with a certain %-value the automatic delay control ADLY is activated. The turn-down of the furnace is made according to the strategy prescribed in the carpet diagram and delay strategy multiplier table. When a stock is discharged from the furnace this is turned-up to the control zone temperatures stored in the carpet diagram according to an exponential curve. The delay strategy multipliers are selected such that the stocks in the soaking zone are correctly heated all time during the automatic delay control.

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 inputs the time to next rolling. The turn-down of all furnace zones is then performed according to an exponential curve to certain temperatures determined by the current product, drop-out interval and given time to next rolling. When the time for turn-down control has elapsed the furnace is turned-up according to a strategy prescribed in the carpet diagrams and multiplier tables. The stocks are not immediately ready for extraction during the manual delay control.

**Feedforward control**

The carpet diagrams make up the hear of the feedforward control block and consist of a number of tables stored in the furnace computer. The tables give the primary optimal settings of the control zone temperatures for the different products as a function of the drop-out interval on steady-state operation. In Table I the carpet diagram of product

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**Figure 3. Zone status interlock of the fuel optimizing control system FOCUS-RF.**

**Notations:**

- MAN = manual heating
- NRM = normal rolling mode
- ORM = open rolling mode (no temperature feedback)
- MRHO = manual reheating (return to ORM)
- MRHN = manual reheating (return to NRM)
- MDLYO = manual delay control (return to ORM)
- MDLYN = manual delay control (return to NRM)
- ADLYO = automatic delay control (return to ORM)
- ADLYN = automatic delay control (return to NRM)
- UP = start-up control
- UPDRY = start-up control ready
- DOWN = turn-down control
- DWNRDY = turn-down control ready
- M = manual status change
- A = automatic status change

The zone status interlock of the fuel optimizing control system is shown in Fig. 3.

**Table I. Carpet diagram of product No. 1 for the walking beam furnace at MEFOS, Metal Working Research Plant in Luleå.**

<table>
<thead>
<tr>
<th>Product No. 1:</th>
<th>Ø 100 × 1500 mm St 37 low carbon steel heated to 1235°C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop-out interval [min:s]</td>
<td>Temperatures [°C]</td>
</tr>
<tr>
<td></td>
<td>Control zone 1</td>
</tr>
<tr>
<td>1:50</td>
<td>1080</td>
</tr>
<tr>
<td>2:00</td>
<td>1040</td>
</tr>
<tr>
<td>2:30</td>
<td>980</td>
</tr>
<tr>
<td>3:00</td>
<td>–</td>
</tr>
<tr>
<td>4:00</td>
<td>–</td>
</tr>
</tbody>
</table>

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No. 1 for the walking beam furnace at MEFOS, Metal Working Research Plant (BTF) in Luleå is given.

A second set of tables, denoted delay strategy multiplier tables, are used to modify the primary optimal control zone temperatures in the following cases

- an unplanned short or long stop caused by production disturbances in the rolling mill
- a planned stop caused by a roll change, repairs or rolling mill adjustment.

The tables for the delay ones for the strategy multipliers are set up analogous to the carpet diagrams. The set-points of the control zone temperatures are obtained by multiplying the primary optimal control zone temperatures, given in the carpet diagrams, with the current delay strategy multipliers. The size of the multipliers depends on the time to next rolling. In Table II the delay strategy multipliers of product No. 1 and drop-out interval 2 min 00 s for the walking beam furnace at MEFOS, BTF is shown.

### Table II. Delay strategy multipliers of product No. 1 and drop-out interval 2 min 00 s for the walking beam furnace at MEFOS, Metal Working Research Plant in Luleå.

<table>
<thead>
<tr>
<th>Product No. 1:</th>
<th>$100 \times 1500$ mm St 37 low carbon steel heated to 1235°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to rolling [min]</td>
<td>Multipliers [-]</td>
</tr>
<tr>
<td>2.0</td>
<td>0.980</td>
</tr>
<tr>
<td>5.0</td>
<td>0.965</td>
</tr>
<tr>
<td>10.0</td>
<td>0.950</td>
</tr>
<tr>
<td>15.0</td>
<td>0.935</td>
</tr>
<tr>
<td>20.0</td>
<td>0.920</td>
</tr>
<tr>
<td>40.0</td>
<td>0.893</td>
</tr>
<tr>
<td>60.0</td>
<td>0.865</td>
</tr>
<tr>
<td>120.0</td>
<td>0.865</td>
</tr>
<tr>
<td>180.0</td>
<td>0.865</td>
</tr>
<tr>
<td>360.0</td>
<td>0.865</td>
</tr>
</tbody>
</table>

#### Temperature predictor

The predictor calculates the mean temperature $\theta_m$, the surface temperature $\theta_s$, and the center temperature $\theta_c$ of the stock as a function of the time using

\[
\frac{d\theta_m}{dt} = \frac{c_m}{\rho \cdot c_p} \left( \frac{\Omega}{A} + \frac{2}{\varepsilon} \right) \varphi
\]

\[
\theta_s = \theta_m + \frac{h \varphi}{c_p \lambda}
\]

\[
\theta_c = \theta_m - \frac{h \varphi}{c_p \lambda}
\]

The density of heat flow rate to the stock from the flue gas ($CO_2$, $H_2O$ and $SO_2$), walls and roof is given by

\[
\varphi = \alpha \left[ \frac{e_s}{1 - (1-e_s) (1-A_p \varphi + \epsilon_{ws} (\theta_s^c - \theta_s^w))} \right] + \alpha_c (\theta_s + \Delta \theta - \theta_c)
\]

(2)

The calculation of the gas emissivity $\theta_s = \epsilon_s (\theta_s, s_{spx})$ and absorptivity $A_p = A_p (\theta_s, \theta_c, s_{spx})$ as a function of the gas temperature $\gamma_g$, the stock surface temperature $\theta_s$, the gas layer thickness $s$ and partial pressures $p_x$ of $CO_2$, $H_2O$ and $SO_2$ is based on analytical expressions given by Schack [10]. The gas radiation from $SO_2$ is included in the $CO_2$-radiation by adding the partial pressure of $SO_2$ to the one for $CO_2$.

The direct-exchange factor between the walls, roof and stock respectively is given by

\[
e_{ws} = e_{sw} \tau_{sw} + \Delta e_{sw}
\]

(3)

where $\Delta e_{sw}$ is a correction factor for flame radiation.

The mean transmissivity of the gas is calculated from

\[
\tau_{gm} = 1 - A_{gm}, A_{gm} = \frac{1}{2} (A_p + A_{sw})
\]

(4)

where $A_{gm}$ is the mean gas absorptivity for radiation from the stock and walls respectively.

The view factor $\beta_{sw}$ is obtained from

\[
\beta_{sw} = \sum_{k=1}^{N} w_k \beta_{sw}^k, \beta_{sw}^k = (\sin \beta'_k - \sin \beta_k)
\]

(5)

For blooms on a plane hearth the calculation of the view factor $\beta_{sw}$ is illustrated in Fig. 4. The weighting factors $w_k$ fulfils

\[
\sum_{k=1}^{N} w_k = 1, \quad w_k \in [0, 1]
\]

(6)

In the mathematical model the furnace is divided into dark and burner zones containing one and only one real or fictive measuring point for gas and wall or roof temperature respectively. From these temperatures, the geometrical and thermal description of the furnace, thermal data of the steel stored in the data base DB and data from the material tracking system the heating curve of the stocks is calculated using Eqs. (1) to (6).

The geometrical and thermal description of the furnace include:

![Figure 4. Blooms on a plane hearth illustrating the calculation of view factors (N = 8).](image-url)
— number of zones, control zones and beams in the furnace
— effective length of the furnace
— positions of zone boundaries, gas, wall and roof thermocouples, first and last stock in the furnace
— indices for dark and burner zones
— indices for furnace temperature profile within the zones (constant or linear continuous profile)
— indices characterizing the heating of stocks within the zones (top-fired, top- and bottom-fired zone, rectangular or circular stocks etc.)
— emissivity of stocks, walls and roof
— percentage number characterizing the fuel mixing (maximum two different fuels)
— gas layer thicknesses and partial pressures of CO₂, H₂O and SO₂ in the zones
— correction factors for flame radiation in the zones
— heat-transfer coefficients and relative gas temperatures for forced convection in the zones.

Thermal data (ρ, cᵢ, and λ) of carbon, low and high alloys steels are also stored in the furnace specific data base DB.

Using finite differences the temperature can also be calculated in e.g. 5 points along a vertical centre line through the stock. This is used when a more accurate calculation of the surface to surface temperature gradient is required.

For each gas temperature an index indicates if the temperature is measured or should be fetched from the wall or roof temperature (furnace temperature) in the same zone according to

\[0 = \text{gas temperature measured}\]
\[j > 0 = \text{gas temperature equals adjusted wall or roof temperature in the same zone (the calculation of the gas bias is based on the fuel flow to control zone)}\]

This also applies to the wall or roof temperature for index 0. For \(j > 0\) this temperature equals the adjusted wall or roof temperature in zone \(j\). However, it is required that the wall or roof temperature is measured in each control zone.

Furthermore, a bias can be added to each temperature for correction of non ideal locations of gas, wall or roof thermocouples.

For each product the ideal heating curves, corresponding to the primary optimal zone temperatures in the carpet diagram, are stored for 3 to 5 different drop-out intervals. The ideal heating curve for product No. 1 and the drop-out interval 2 min 00 s is given in Table III for the walking beam furnace at MEFOS, BTF. The used set-points of the zone temperatures are 1040, 1235 and 1235°C according to Table I.

For the walking beam furnace at MEFOS, BTF calculated and measured temperatures, when heating Ø 100 × 1500 mm St 37 low carbon steel to 1235°C during constant furnace conditions, are shown in Fig. 5. Drop-out intervals and control zone temperatures are chosen according to Table I.

### Heat content

The heat contents of a stock is calculated from the mean temperature \(θ_m\) using

\[h = c_p \theta_m\] (7)

<table>
<thead>
<tr>
<th>Length [m]</th>
<th>Temperature [°C]</th>
<th>Length [m]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>20</td>
<td>4.638</td>
<td>887</td>
</tr>
<tr>
<td>0.400</td>
<td>20</td>
<td>4.964</td>
<td>984</td>
</tr>
<tr>
<td>0.726</td>
<td>69</td>
<td>5.290</td>
<td>1061</td>
</tr>
<tr>
<td>1.052</td>
<td>139</td>
<td>5.616</td>
<td>1111</td>
</tr>
<tr>
<td>1.378</td>
<td>205</td>
<td>5.942</td>
<td>1145</td>
</tr>
<tr>
<td>1.704</td>
<td>267</td>
<td>6.268</td>
<td>1185</td>
</tr>
<tr>
<td>2.030</td>
<td>330</td>
<td>6.594</td>
<td>1206</td>
</tr>
<tr>
<td>2.356</td>
<td>399</td>
<td>6.920</td>
<td>1223</td>
</tr>
<tr>
<td>2.682</td>
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<td>1237</td>
</tr>
<tr>
<td>3.008</td>
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<td>632</td>
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</tr>
<tr>
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</tr>
<tr>
<td>3.986</td>
<td>742</td>
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<td>1252</td>
</tr>
<tr>
<td>4.312</td>
<td>800</td>
<td>9.000</td>
<td>1252</td>
</tr>
</tbody>
</table>

### Feedback control

The feedback control block consists of separate PI-controllers, whose input signals are the integral of a weighted difference between the calculated and ideal heat contents over the considered control zones.

### Pacing control

The heating curve of the stocks is much more sensitive to changes in the throughput than to changes in the control zone temperatures. By making small changes in the throughput as well as the control zone temperatures deviations in stock temperatures from the ideal heating curve can be eliminated more quickly than by making feedback to the control zone temperatures alone. The system adjusts the drop-out interval such that the deviation from the total ideal heat content is minimal taking into account the requirement on the drop-cut temperature. Feedback control from a pyrometer measuring the stock surface temperature in the rolling mill is included. The working range of the drop-out interval is limited. Operator correction of the drop-out interval is possible.

The function is used to synchronize the production in the furnace and the rolling mill. Both the furnace and the rolling mill capacity can be the limiting factor. The drop-out interval is adjusted down when the control zone temperatures, the fuel flows or the waste gas temperature are too high.

### Programmed start-up and turn-down control

A special strategy is included to account for very long stops such as weekend starts-up or turns-down and stop shifts. In those cases the steel temperatures are no longer critical. It is just a question of bringing the furnace from a cold or turn-down state up to rolling temperature or vice versa. The operator specifies zone-wise the holding or operating
temperature and the heating time. The set-point of each control zone temperature is then changed between the holding and operating temperature according to the exponential curve

\[ \theta = \theta_1 + (\theta_h - \theta_1) e^{-\frac{t}{T}}, \quad \theta_1 = \frac{1}{2^n - 1} (2^n \theta_o - \theta_b) \]  

(8)

The time constant \( T \) is calculated from the heating time according to

\[ T = \frac{t_{1/2}}{n \cdot \ln 2} \]  

(9)

where

\[ n = \frac{t_{1/2}}{t_{1/2}} \]

number of half-lifes \( t_{1/2} \) during \( t_{1/2} \), \( n \in (0, \infty) \)

Figure 5. Calculated and measured temperatures when heating \([1] 100 \times 1500 \text{ mm St 37 low carbon steel to } 1235^\circ \text{C in the walking beam furnace at MEFOS, Metal Working Research Plant.} \]

The choice of \( n \) essentially affects the heating curve. For large values of \( n (n \geq 5) \) large changes of the set-point are obtained during the initial period of the start-up control and small changes during its end. Small values of \( n (n \leq 1) \) give an almost constant change of the control zone temperature during the whole start-up control.

An analogous description holds for the turn-down control. The interlock of the zone status for start-up and turn-down control is shown in Fig. 5.

Logging and alarm

In order to improve the production schedules, develop and follow up the furnace control system the following production reports and engineering logs are available in the system

- shift report
weekly production report
- stop time log
- energy distribution log.

The shift report contains information about the number of extracted stocks, extracted tonnes and extracted tonnes per effective time, the average thickness of the stocks, the hearth cover, total and specific energy consumption (kWh/ton), energy consumption per effective time (kWh/effective time), number and length of stops, computer availability etc. on an hourly basis. The weekly production report is an assembly of the shift reports on a weekly basis.

The stop time log contains information about the distribution of the stop times, the total length and number of stops on a shift basis.

In the energy distribution log the specific energy consumption can be read off as a function of the hearth cover and the average stock thickness on a weekly basis.

Adequate provision is made in the system for alarm to advice the operator about incongruous values, anomalous situations or malfunctions of the measurement devices and tracking sensors. These alarms are printed out on the alarm printer in the control room.

### Core memory requirements

In the General Automation GA-16/240 satellite computer, controlling the 3 ton/hr top-fired walking beam furnace at MEFOS, BTF, with one operator VDU, one alarm printing terminal and communication interfaces to local Honeywell TDC 2000 micro-computer, SATT-Electronics PBS-mini computer and main process computer GA-945, the core disposition is given below:

<table>
<thead>
<tr>
<th>Component</th>
<th>Memory Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating system Control II</td>
<td>14 k word</td>
</tr>
<tr>
<td>Process interface PROVAL</td>
<td>17 k word</td>
</tr>
<tr>
<td>Furnace specific data base DB</td>
<td>3 k word</td>
</tr>
<tr>
<td>Application programs</td>
<td>18 k word</td>
</tr>
<tr>
<td>Operator communication DBOP</td>
<td>12 k word</td>
</tr>
<tr>
<td></td>
<td><strong>64 k word</strong></td>
</tr>
</tbody>
</table>

Compared to an industrial application the furnace specific data base of this system is relatively small.

In the process interface PROVAL possibilities are at hand to log and store a larger number of analogue and digitized signals and calculated values with different time scales on the main process computer GA-945.

### Application

The fuel optimizing control system has been in operation since August 1982 on the 100 ton/hr top-fired walking beam furnace of roughing mill No. 2 at Swedish Steel AB, Luleå. The application programs were implemented in a double computer system PDP 11/24 together with a new DDC burner control system, a position and sequence control system and an advanced system for material tracking including a data link to a central computer for production planning.

In the mathematical model of the furnace the heating zone is divided into one burner zone and two dark zones while the soaking zone is divided into one burner zone and one dark zone as illustrated in Fig. 6. The temperature is measured in the roof in all three dark zones, both burner zones and in the waste gas flue using thermocouples. In the 1st and 2nd dark zone and both burner zones the furnace temperature profile is assumed to be linear continuous while in the 3rd dark zone the temperature profile is assumed to be constant.

The specific fuel consumption before and after the installation of the furnace computer control system is shown in Fig. 7. The straight lines in the figure indicate the expected fuel consumption in manual control MAN (with correct carpet diagrams) and in the normal rolling mode NRM.

During the period 198214-8224 the mean fuel consumption was 448 kWh/ton. With the new burner control system and correct carpet diagrams the fuel consumption is expected to decrease to 390 kWh/ton (13 %) and further decrease to 350 kWh/ton (another 13 %) with the system in the normal rolling mode NRM. Totally, an overall fuel saving of 26 % is thus expected.

The installation of the furnace computer control system has also led to a decrease in scale losses, better uniformity of bloom temperatures and an improvement of production quality. The furnace staff have had a positive experience of the system. Today they have a much better overview of the furnace operation with respect to steel and furnace temperatures, O₂-contents, furnace pressure and fuel consumption.
**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>h</td>
<td>height of stock</td>
<td>(m)</td>
</tr>
<tr>
<td>ℓ</td>
<td>length of stock</td>
<td>(m)</td>
</tr>
<tr>
<td>Ω</td>
<td>circumference of cross section A</td>
<td>(m)</td>
</tr>
<tr>
<td>s</td>
<td>gas layer thickness (average mean beam length for gas-surface exchange)</td>
<td>(m)</td>
</tr>
<tr>
<td>A</td>
<td>cross section of stock</td>
<td>(m²)</td>
</tr>
<tr>
<td>V</td>
<td>volume of stock</td>
<td>(m³)</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
<td>(s)</td>
</tr>
<tr>
<td>θ</td>
<td>temperature</td>
<td>(°C)</td>
</tr>
<tr>
<td>Ψ</td>
<td>temperature</td>
<td>(K)</td>
</tr>
<tr>
<td>Δθg</td>
<td>difference between temperature of the gas near the stock and roof respectively</td>
<td>(°C)</td>
</tr>
<tr>
<td>ρ</td>
<td>density of heat flow rate</td>
<td>(W/m²)</td>
</tr>
<tr>
<td>ρg</td>
<td>partial pressure of gas component x</td>
<td>(atm)</td>
</tr>
<tr>
<td>ρc</td>
<td>density of stock</td>
<td>(kg/m³)</td>
</tr>
<tr>
<td>c_v</td>
<td>specific heat capacity of stock</td>
<td>(J/kg °C)</td>
</tr>
<tr>
<td>c_θ</td>
<td>mean specific heat capacity of stock</td>
<td>(J/kg °C)</td>
</tr>
<tr>
<td>λ</td>
<td>thermal conductivity of stock</td>
<td>(W/m °C)</td>
</tr>
<tr>
<td>h</td>
<td>specific enthalpy of stock</td>
<td>(J/kg)</td>
</tr>
<tr>
<td>α_h</td>
<td>heat-transfer coefficient by forced convection</td>
<td>(W/m² °C)</td>
</tr>
<tr>
<td>ε_s</td>
<td>emissivity of stock</td>
<td></td>
</tr>
<tr>
<td>ε_w</td>
<td>emissivity of walls</td>
<td></td>
</tr>
<tr>
<td>ε_g</td>
<td>emissivity of gas</td>
<td></td>
</tr>
<tr>
<td>A_g</td>
<td>gas absorptivity for radiation from stock</td>
<td></td>
</tr>
<tr>
<td>A_w</td>
<td>gas absorptivity for radiation from walls</td>
<td></td>
</tr>
<tr>
<td>A_m</td>
<td>mean gas absorptivity for radiation from stock and walls</td>
<td></td>
</tr>
<tr>
<td>τ_m</td>
<td>mean gas transmissivity for radiation between stock and walls</td>
<td></td>
</tr>
<tr>
<td>β_g</td>
<td>view factor between walls, roof and stock respectively</td>
<td></td>
</tr>
<tr>
<td>e_w</td>
<td>∈ [0, 1]</td>
<td></td>
</tr>
<tr>
<td>β_w</td>
<td>∈ [0, 1]</td>
<td></td>
</tr>
<tr>
<td>Δε_w</td>
<td>correction factor for flame radiation</td>
<td></td>
</tr>
<tr>
<td>σ</td>
<td>Stefan-Boltzmann's constant</td>
<td>(W/m²K⁴)</td>
</tr>
<tr>
<td>n</td>
<td>number of half-lives during start-up or turn-down control</td>
<td>(s)</td>
</tr>
</tbody>
</table>

**Indices:**

- s: surface
- c: center
- g: gas
- w: wall
- m: mean
- o: operating
- h: holding
- rdy: ready

**Constants:**

- σ = 5.6697 · 10⁻⁸ Stefan-Boltzmann's constant (W/m²K⁴)
- n ∈ (0, ∞) number of half-lives during start-up or turn-down control

**References**


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