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Slab Temperature Control for Reheating Furnaces

Literature review

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Abstract

This report contains an introduction to classical and present furnace control. To give a basic understanding of the control problem a description of the reheat furnace no. 2 at The Danish Steel Works Ltd is first given. After this, the slab heating process is analyzed and models for the mean temperature and temperature distribution are described. The analysis shows that there is a conflict between obtaining a large furnace capacity on one side and having low energy consumption and small temperature gradients on the other side. These results show why it is worthwhile to use advanced control strategies for controlling the reheat furnaces.

After the analysis of the heating process, the state of the art furnace control systems is described. Since it is not possible to measure the slab temperature, prediction models are used when controlling this variable. The set points for the furnace temperatures are generated based on the estimated slab temperatures. Among other difficulties the furnace temperature is used for controlling several slab temperatures. This makes a careful choice of the furnace temperature necessary. Other functions of the slab temperature control systems are special strategies for production delays and pacing systems for coordination between furnace and rolling mill operation.

In the literature review, short resumes of 31 papers and journal articles are given. The key figures show that it is possible to obtain slab temperatures within an accuracy of 50 degrees C and energy saving of 5% to 20%. This gives another explanation for the success of the model based level II slab temperature control systems. The current tendency of the work on slab temperature control seems to go in the direction of pacing systems and more advanced modeling and control of the reheating process

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Contents

Preface

This literature review has been made during the fall of 1998 in connection with my work on reheat furnace control system. It contains a review of about 31 articles relevant for the slab temperature control problem. The report is primarily directed towards control engineers with interest in reheating process.

The work has been supported financially by The Danish Steelworks Inc., where I am employed. The work has mainly been done at the Department of Automatic Control at Lund Institute of Technology, Sweden. I wish to express my gratitude to Björn Wittenmark, Bo Bernhardsson, and Hans Wennerberg for their valuable comments on this manuscript.

LARS MALCOLM PEDERSEN

1. Introduction

The purpose of this report is to give a short introduction to control of reheat furnaces in the steel industry. It is therefore mainly directed toward giving a physical understanding of the reheat furnace operation and a basic understanding of the present furnace control algorithms. The reheat furnace no. 2 at The Danish Steel Works Ltd. will be used as an example throughout the report.

First a fairly general description of reheat furnaces is given. The section is ended by a more specific description of furnace no. 2 at The Danish Steel Works Ltd. Then simplified models for the slab heating are derived and these models are used for an analysis of the slab reheating process. After the analysis a description of the state of the art of reheat furnace control systems is given and this description serves as an introduction to the literature review which can be found in the final part of this report.

2. Reheat furnaces

The main purpose of a reheat furnace is to heat *slabs* [1] (steel blocks which are raw material for the plate rolling mill) from a temperature around 20°C to a temperature of approximately 1250°C before they are processed in the rolling mill. The reheating furnaces are typically large box shaped structures which are heated by a large number of oil or gas *burners* placed in the furnace floor, roof, or walls. The interior of the furnace is build using special made ceramic bricks.

The fuel is mixed with a suitable amount of air in the burners before it is combusted in the furnace, and the exhaust gases leave the furnace through the *stack*. The stack is most commonly placed in the charge side of the furnace to ensure a maximal utilization of the hot air from the burners. Before the exhaust air is released it is passed through a *recuperator* where it is used to heat the incoming air to the burners. To prevent cold air from entering the furnace the *furnace pressure* is kept a small amount over the atmospheric pressure. This is obtained by controlling the flow through the stack. Due to formation of **scale**, which is a result of an oxidation of the slab surface, it is sometimes attempted to control the *oxygen content* of the furnace atmosphere. The scale formation usually consumes several percent of the steel volume heated by the furnace.

The slabs enter the furnace at the *charge end* and leave the furnace at the *discharge end*. The slabs are transported through the furnace by water cooled walking beams, if it is a *walking beam furnace*, or pushed through the furnace on water cooled skids, if it is a *pusher furnace*. The transport systems cools the slabs locally and the result is *skid marks*, which are cold zones at the bottoms side of the slabs. Some furnaces do not have a slab transport system, instead the slabs are charged and discharged using a crane, these furnaces are called *batch furnaces*.

When operating the furnace temperature three things are given much attention

- **Slab temperature.** This includes slab *mean temperature*, *temperature*

[1] Raw materials for section rolling are heated in similar furnaces, these steel blocks are called *billets*.

gradient in the thickness direction, and skid marks.

- **Furnace throughput.** This covers the number of tons per hour heated by the furnace.
- **Fuel consumption.** As can be imagined the furnaces use large amounts of energy for heating the slabs. Therefore, it is important that the slabs are heated using as little energy as possible.

The most important thing in furnace control is to heat the slabs to the specified temperature profile with a minimal energy consumption. The furnace capacity is more or less given by the furnace design, but can of course also be affected by the control system. An analysis and discussion of the furnace characteristics with respect to capacity, slab mean temperature and energy consumption will be given in Section 3, while the control systems for the slab heating is described in Section 4.

3. Analysis of heating process

In the following we will have a look at the furnace throughput, slab temperature profile, and furnace energy consumption. We start with a model for the slab temperature profile in its most general form.

In the literature the slab temperature distribution is often described by a one dimensional partial differential equation, where it is assumed that the heating is mainly due to radiation and convection from gas, furnace walls and roof. Using the one dimensional model implies that it is assumed that the temperature of the individual slab does not vary in the length or in the width direction. Assuming that there is no heat transport through the slab sides this is a valid assumption.

The model shown in Figure 2 can be described by the one dimensional partial differential equation

$$\begin{aligned} h\rho(T)c_p(T)\frac{\partial T}{\partial t}(x,t) &= \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}(x,t)\right) \\ \lambda(T)\frac{\partial T}{\partial x}(0,t) &= q_b(t) = \lambda_b(T(0,t) - T_b(t)) \\ \lambda(T)\frac{\partial T}{\partial x}(h,t) &= q_t(t) = \sigma\epsilon_t(T_t(t)^4 - T(h,t)^4) + \lambda_t(T_t(t) - T(h,t)) \\ T(x,0) &= T_o(x) \end{aligned} \tag{1}$$

where T is the temperature distribution of the slab dependent of position x and time t. The slab thickness is denoted by h, ρ is the specific mass of steel, c_p is the specific heat capacity of steel, λ is the heat conductivity of steel, all dependent on the slab temperature T. σ is Boltzmanns constant, and ϵ_t is the emissivity of the slab top side. T_o is the initial temperature distribution dependent of x, T_b is the temperature below the slab and T_t is the temperature over the slab. λ_t and λ_b are the heat transfer coefficients for the slab top and bottom respectively. A simpler version of (1) is often used for modeling slab temperature, see [Rixin and Baolin, 1992] and [Hollander and Zuurbier, 1982]. Since the slab is mainly heated from the top the radiation term at the slab bottom is left out in the model.

The example used throughout this report is the no. 2 reheat furnace at The Danish Steel Works Ltd. which is a 46 m long walking beam furnace which is heated by 33 gas burners placed in the furnace wall and roof. This implies that the slabs are mainly heated from the top side. The maximal capacity of the furnace is 130 ton/hour and it normally takes about 5 hours to heat a 260 mm slab. Under normal operation the furnace contains approximately 60 slabs.
The furnace has three parallel tracks and the slabs are transported through the furnace by three independent sets of beams lifting the slabs and transporting them forward in steps. In the following we will only consider one track and will therefore consider the furnace a two dimensional phenomenon. A schematic diagram of the furnace is shown in Figure 1. The slabs enter at the left side of the furnace and leave through the right side.
The furnace is divided into 5 control zones as indicated in the figure. Zone 0 is a non controlled zone, while Zone 1 is side fired and Zones 2, 3, and 4 are top fired. The arrows show the main direction of the air flow through the furnace. The furnace temperature is measured in nine points by thermocouples placed in the furnace roof with one thermocouple placed over each track. This implies that there are three thermocouples in the width direction in each measurement point. Normally the mean values of these three thermocouples are used as the furnace temperature measurement values. The thermocouples with the dark frame are used for controlling the zone temperature while the thermocouples with light frame are only used for measurement for the slab temperature control system. When controlling the furnace temperature it is assumed to be constant in each zone.
At the furnace no. 2 at The Danish Steel Works the furnace temperatures are controlled by an ABB FICS system. The slab temperatures are controlled by an ABB FOCS system which calculates the slab temperatures from material data, temperature readings from the thermocouples, and the air and gas flows to the burners.

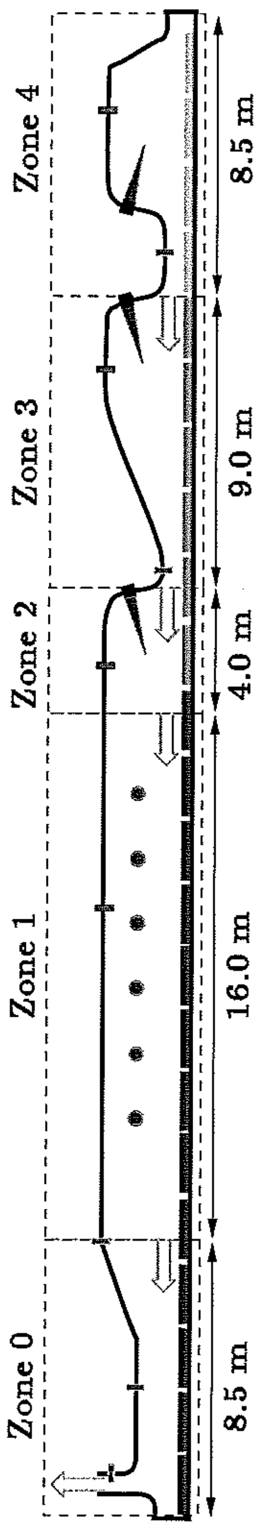

Figure 1 A schematic diagram of the reheat furnace no. 2 at The Danish Steel Works Ltd.

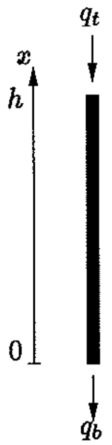

Figure 2 Illustration of the model for the slab temperature (2). The figure illustrates that the rod is heated from the top and bottom with the heat intensity q_t and q_b respectively.

In the following analysis of the slab heating process, the slab thickness is chosen to 260 mm which is the maximal value for the reheat furnace no. 2 at The Danish Steel Works Ltd. As will be seen from the analysis, 260 mm slabs have the longest heating times and the largest temperature gradients and can therefore be seen as the worst case with respect to these characteristics.

3.1 Furnace capacity and slab temperature

We now assume that the slab temperature T is uniform in the thickness direction and that the parameters ρ, c_p, and λ are independent of T. We also say that all heat is transferred to the top side of the slab by radiation The last assumption is often employed in the analysis of the slab heating problem, see for instance [Fontana *et al.*, 1983].

Under the above assumptions (1) reduces to

$$\begin{aligned} h\rho c_p \frac{dT}{dt}(t) &= \sigma\epsilon_t(T_t^4(t) - T^4(t)) \\ T(0) &= T_o \end{aligned} \qquad (2)$$

The solution for (2) gives interesting qualitative information about the heating process. Defining $t_{0.99}$ as the time where the slab has reached 99 % of the furnace temperature T_t we have the equation

$$\frac{h}{t_{0.99}} \propto \frac{\sigma\epsilon_t}{\rho c_p} \int_0^1 T_t^3(t_{0.99}\tau)d\tau \qquad (3)$$

where $\propto$ means *proportional to.* Since the furnace throughput can be approximated by $h/t_{0.99}$ and we see from (3) that the furnace capacity is proportional to T_t^3 if the shape of the furnace temperature as a function of time t is kept constant. This implies that the furnace capacity increases dramatically with increased furnace temperature. Note that an increase of the furnace temperature T_t will result in both shorter heating times $t_{0.99}$ *and* higher slab temperatures.

3.2 Temperature gradient

An other aspect of the slab heating is that the slab temperature should be uniform throughout the slab thickness. To have a homogeneous slab temperature it is necessary that the slab spends a sufficiently long period of time at an elevated temperature. To investigate this subject we return to (1).

To be able to solve this equation we investigate the case when the coefficients are independent of the slab temperature T and the heating is performed by convection only. It would be nice to be able to perform the analysis for heating by radiation, but to be able to solve the PDE it is necessary assume heating by convection and then linearize the boundary conditions in a working point.

$$\begin{aligned} h\rho c_p \frac{\partial T}{\partial t}(x,t) &= \lambda \frac{\partial^2 T}{\partial x^2}(x,t) \\ \lambda \frac{\partial T}{\partial x}(0,t) &= \lambda_b(T_b(t) - T(0,t)) \\ \lambda \frac{\partial T}{\partial x}(h,t) &= \lambda_t(T_t(t) - T(h,t)) \\ T(x,0) &= T_o(x) \end{aligned} \tag{4}$$

The model (4) has also been used for slab temperature modeling, see [Yang and Lu, 1988]. Since we have only heating from the top in our case we set $\lambda_b = 0$ in the following.

The solution of (4) is

$$T(x,t) = T_t + (T_o(x) - T_t) \sum_{k=1}^{\infty} \gamma_k \cos(\beta_k x) e^{-\frac{t}{\tau_k}} \tag{5}$$

where the largest time constant τ_1 is limited from below by

$$\tau_1 \geq \frac{4\rho c_p h^3}{\lambda \pi^2} \approx 20.0 \text{ min} \tag{6}$$

this implies that it takes at least 60 minutes for the temperature of the slab bottom $T(0,t)$ to be 95 % of the temperature of the slab top $T(h,t)$. It is interesting to note that τ_1 is proportional to h^3, this implies that the increase in thickness from for instance 0.2 m to 0.26 m implies that the lower limit for the time constant of the differential temperature increases more than a factor two.

Since the total heating time of the slab is around five hours we conclude that it is important to consider the temperature gradient of the slabs when designing the heating strategy to obtain slabs with a small temperature gradient at the end of the heating process. That the slabs should have a residence time of one hour at the end of the heating period implies that their mean temperature is not increased in this period, therefore the demands on the temperature gradient reduces the furnace capacity.

3.3 Energy consumption

The energy used for heating slabs to the specified temperature can not be affected by the furnace control system. But as will be seen from the following it will be possible to affect the heat losses from the furnace. The energy losses may be divided into losses from the furnace structure and losses through the exhaust gases. Since the temperature profile of the furnace is relevant we introduce the furnace temperature T_t as a function of position in the furnace length direction z.

Assuming steady state the conduction and convection losses through the furnace structure q_c are proportional to

$$q_c \propto \int_0^l (T_t(z) - T_a)\, dz$$

where T_a is the ambient temperature and l is the furnace length. Since $T_t \gg T_a$ the argument of the integral will always be positive and we therefore conclude that the heat losses will increase with increasing gas temperature everywhere in the furnace. We therefore want the furnace temperature to be as low as possible.

The heat losses through the exhaust gases are proportional to

$$q_s \propto \dot{m}(0)T_t(0)$$

where the mass flow of the gas, $\dot{m}$, depends on the position z. We here see that higher temperatures and flows in the stack increases the energy losses of the furnace. Most reheat furnaces are *counter flow furnaces* which means that the stack is placed in the charge end of the furnace. The energy consumption can then be minimized by ensuring that the furnace temperature in the charge end is as low as possible.

4. State of the art

From the above analysis we have seen that controlling the slab temperature involves several obvious conflicts with respect to furnace capacity and energy consumption. The slab temperature control problem is furthermore complicated by the fact that it is not possible to measure the slab temperature and that the temperatures of several slabs should be controlled by one furnace zone temperature. This is the main explanation of why the complex control systems described in this section have been implemented on the majority of reheat furnaces in the steel industry.

The reheat furnace control systems are normally divided into a furnace temperature control system and a slab temperature control system. These systems are referred to as *level I* and *level II* systems respectively. Since their functionalities are very different they are described separately below.

4.1 Furnace temperature control (level I)

As stated above the main tasks of the level I control system is to control the furnace temperature. Usually, also a separate control of the furnace pressure is included and control of the furnace oxygen content is also reported. Beside these control tasks the level I system normally also handles automatic start up and shut down of the furnace, sequential control of the slab transportation system, protection of equipment etc. Since the main purpose of this report is to describe the slab temperature control these tasks will not be described here.

The furnace temperature control is handled by dividing the burners into a number of groups. The air and fuel flows to all burners in one group are then controlled using the temperature measurement from one or more thermocouples placed in the zone. The zone temperature controllers set the reference

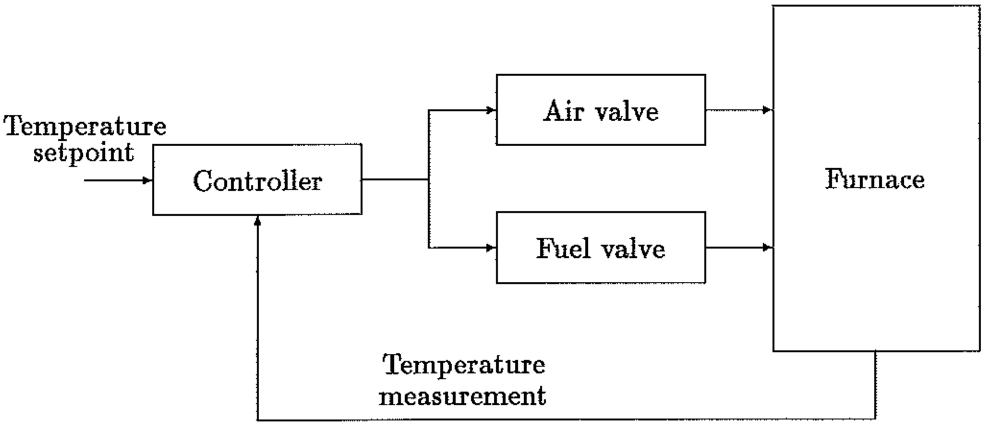

Figure 3 Principal diagram of the level I furnace temperature control. The temperature controller sets the references to the air and fuel control loops.

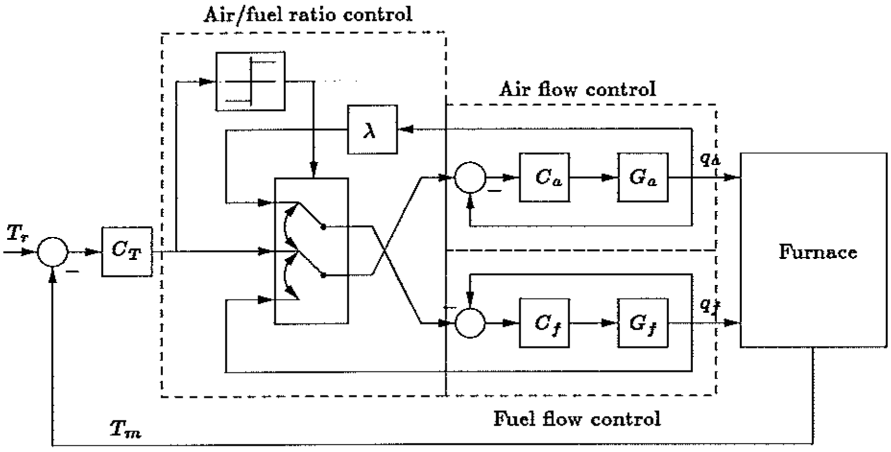

Figure 4 Block diagram for the cross coupled lead/lag air and fuel flow control algorithm. The algorithm ensures that there always is excess air present, both when the air/fuel flow is increased and decreased. In the figure T_r is the temperature reference T_m is the measured furnace temperature, q_a is the air flow, q_f is the fuel flow, C_T is the temperature controller, C_a is the air flow controller, C_f is the fuel flow controller, G_a is the transfer function of the air supply system, G_f is the transfer function of the fuel supply system and λ is the desired air/fuel ratio.

value to the air and fuel controllers, see Figure 3. The zone temperatures are normally controlled independently of each other, despite the fact that the control problem is multivariable due to the flow between the zones.

When controlling the air and fuel flows it is important that the air/fuel ratio is appropriate. If the air/fuel mixture is to rich the fuel is not combusted properly and poisonous gases are produced. If the burner on the other side is operated with excess air, an amount of air is heated unnecessarily. Normally, the burner is operated with a small amount of excess air to ensure that the fuel is completely combusted. The air and fuel flows are normally controlled using the cross coupled lead/lag concept shown in Figure 4, see [Carpenter and Proctor, 1987].

Using the control scheme shown in Figure 4 the air leads the demand for fuel when the temperature controller demands more flow, and the fuel controller leads the air demand when the temperature controller demands less flow. The advantage of the algorithm is that it is ensured that excess air always is present. A more tight control of the air/fuel ratio is therefore possible, see also [Åström and Hägglund, 1995]. Since it is hard to measure the furnace oxygen content the air/fuel ratio λ is adjusted dependent of the fuel flow rate, since furnaces leaks normally provide additional air for low air/fuel flows.

Some of the burner control systems also contain algorithms for control of the furnace oxygen content. These are, however, often reported to be out of operation, since a proper measurement of the oxygen content of the furnace atmosphere is very difficult.

Normally, the level I control also provides a furnace pressure control. The purpose of the pressure control is to provide a constant furnace pressure despite variation of the air and fuel flow to the burners etc. The pressure is normally controlled using a measurement from a pressure sensor placed near the furnace discharge door. The pressure is controlled by varying the flow through the stack, this can either be done using a fan or a damper placed in the stack.

4.2 Slab temperature control (Level II)

The main task of the level II systems is control of the slab temperature to ensure proper heating quality and minimal energy consumption. The slab temperatures are controlled by varying the furnace temperatures. The minimal energy consumption is achieved by heating the slab as close as possible to the specified temperature. The desired slab temperature reference is called the *heating curve* and is normally dependent on the slab position in the furnace, furnace throughput, etc.

The furnace temperatures are controlled to obtain the maximal heat input as far away from the stack as possible. In this way the heat absorption of the slabs is maximized, see [Fontana *et al.*, 1983]. The level II systems normally also include a function for material handling to keep track of slab positions and material quality. This function is necessary to control the slab temperature but is not a control function and it will therefore not be described here.

A general problem in slab temperature control is that it is not possible to obtain a proper measurement of the slab temperature. The surface temperature of the slabs can, however, be measured using radiation pyrometers. A disadvantage of this measurement is that if the slab has a large temperature gradient, as discussed in Section 3, the surface temperature will not be a true measure of the mean slab temperature. It is also possible to measure the surface temperature in the rolling line where the steel temperature usually is more homogeneous, in this case there will be a considerable time delay between heating and temperature measurement, see [Schurko *et al.*, 1987].

Due to the difficulties in the slab temperature measurement alternative ways have been found for controlling the slab temperature, these are

- **Feedforward control**, where the furnace temperature set points are found on tables based on production rate and material data.
- **Feedback control**, where the furnace temperature set points are found from slab temperatures calculated using a model and the heating curves.

The feedforward control generates set points to the level I zone temperature

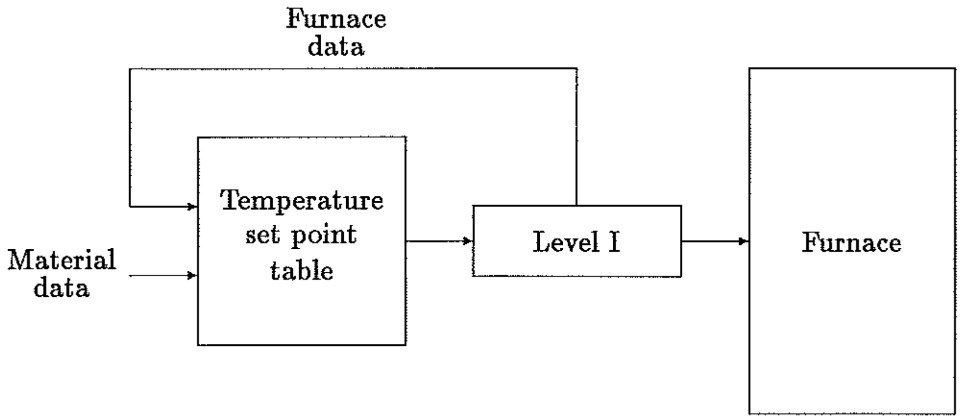

Figure 5 Principal diagram for the feedforward level II control algorithm. The algorithm calculates the set points for the zone temperature controller based on loop up tables with furnace and material data as inputs.

controllers dependent on production rate and material qualities in the furnace, see Figure 5. The set points are found using look up tables which usually are generated using an off line simulation program, see [Hollander and Zuurbier, 1982], and [Glatt and Macedo, 1977]. The control strategy usually includes a delay strategy, where the furnace temperature is lowered during stops. The major disadvantage of these strategies is that they are not well suited for transient control of the furnace, see [Schurko *et al.*, 1987]. The reason for this is that the look up tables are generated for steady state operation.

The feedback slab temperature control algorithms use an on-line model for estimating the slab temperatures. The model is normally close to a discretized version of (1). The slab temperature is calculated using the temperature measurements from thermocouples in the furnace walls and the air and fuel flows to the burners. In the temperature calculation the temperature is normally assumed to vary linearly between the measurement points.

Normally, the estimated slab temperatures are compared to heating curves which can be generated by off-line simulations, see [Leden, 1986], or by an online optimization algorithm, see [Yoshitani *et al.*, 1991]. The heating curves are dependent of production rate and material parameters. The level II system also includes a production *delay strategy* where the furnace temperature is lowered during production stops. Some systems lowers the zone temperatures based on look up tables, others control the slab temperatures during delays, see [Hutchison and Passano, 1990]. Other functions in the level II system include estimation of cold zones in the slabs due to cooling by the slab transport system, see [Roth *et al.*, 1986] and surveillance of the furnace operation by on-line calculation of the heat balance for the furnace, see [Fontana *et al.*, 1983]. A diagram for the feedback level II scheme is shown in Figure 6

Some systems also feature a pacing control where the production rate is controlled automatically based on the maximal capacity of the furnace and the rolling line, see [Fontana *et al.*, 1983]. The pacing control system is one of the functions in a level III system used for controlling the production flow in the plate mill.

Based on the slab temperature deviations from the heating curve the level II

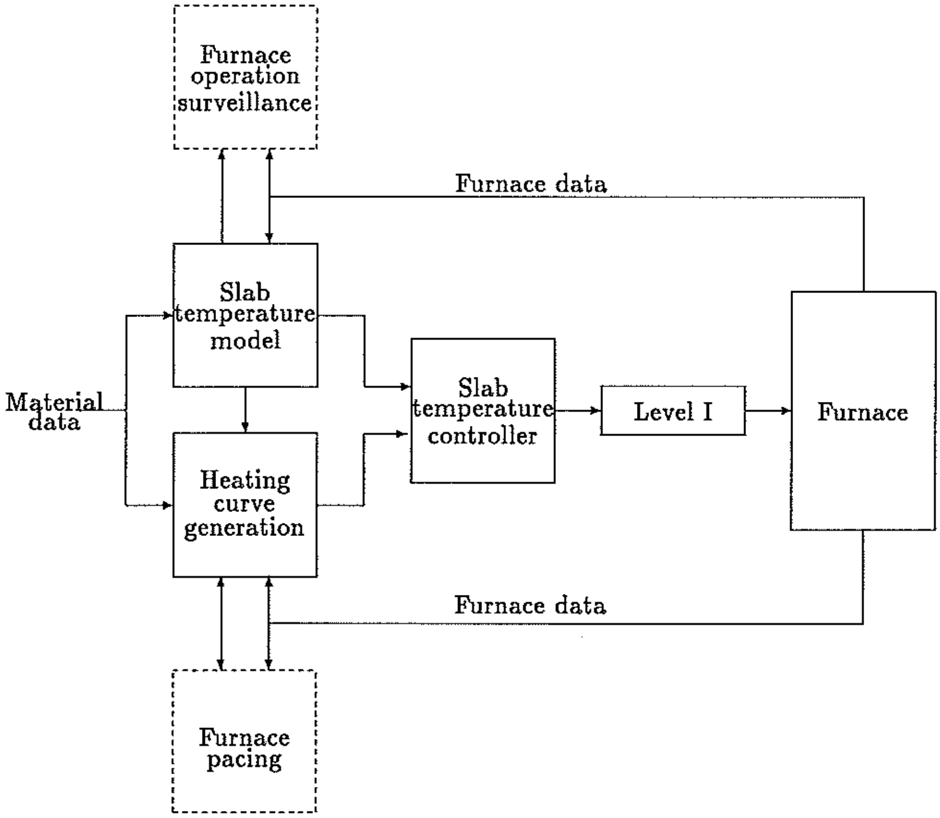

Figure 6 Schematic diagram for the level II feedback control. The slab temperature controller sets references to the level I control system on the basis of a slab temperature calculated from furnace data and a heating curve. Possible additional functions are pacing of the rolling line, i.e. automatic control of the rolling line production rate, and furnace operation surveillance based on on-line computations of the furnace heat balances.

system sets references to the level I system. Normally, the level II system computes the temperature references for the zone temperature controllers of the level I system, but some systems calculate the necessary fuel supplies and control the air and fuel flows directly. One common problem for the level II system is that despite that the temperature control zones of the furnace contains many slabs, it is only possible to specify one temperature set point for each zone.

5. Literature review

In the following a survey of the relevant articles found in literature searches at the *Technical Knowledge Center & Library of Denmark* in 1995 and at The Department of Automatic Control, Lund in 1998 is given. The latest search were done using the COMPENDEX database, the INSPEC database , the SCIENCE CITATION INDEX, and the U.S. PATENTS database. Generally the INSPEC data base provided the best result with a search first on *furnace*, *control*, and *steel* and then excluding irrelevant references. The author estimates that this review includes approximately 30% of the available articles on slab temperature control of reheat furnaces.

The references suggest the following division of time periods

1966 – 75 **The early years.** In this period the first reports on computer control of reheat furnaces are given.

1975 – 86 **The golden period.** An indication of this, is that 17 of 25 US patent applications are from this period. The development of computer power combined with the oil crisis seems to have triggered the development of the slab temperature control systems.

1986 – 98 **Spreading the technology.** In this period the most of the systems seem to be implemented on the reheat furnaces in the steel industry.

The latest literature search indicates that the research is now directed toward the use of more advanced modeling and control methods and further development of level III systems. Suggested reading about the slab temperature control includes [H. E. Pike and Citron, 1970], [Glatt and Macedo, 1977], [Fontana *et al.*, 1983], [Leden, 1986], [Yoshitani *et al.*, 1991], and [Kusters and van Ditzhuijzen, 1994].

The literature survey is based on 31 articles, which are divided into the following main groups

- Modeling
- Furnace temperature control (level I)
- Slab temperature control (level II)

It should be recognized that it sometimes is hard to group the articles in this way. For instance, some of the articles on level II control also contain a great deal of modeling. The articles are listed in chronological order in each of the sections mentioned in the above list.

In the review a short summary of the functionality of the model and control strategy is given and the following standard items are listed

- Furnace type
- Furnace capacity
- Number of zones
- Developed by
- Implemented at
- Temperature accuracy of model
- Fuel savings
- Controller types

whenever data is missing the point will be left out in the table.

5.1 Modeling

[Ogawa, 1975]

Developed by	Hirohata Works, Nippon Steel Corp., Japan
Implemented at	Hirohata Works, Nippon Steel Corp., Japan

This paper describes a method for reducing a one dimensional PDE to an ODE. The method preserves more structure of the PDE compared to the finite difference method, which makes it possible to make the ODE model more compact. The nonlinear PDE for the slab heating is first linearized in a working point and the linear PDE is then approximated with a linear time varying difference equation. The error obtained in connection with the approximation is within $\pm 1\%$.

[Gray *et al.*, 1978]

Furnace type	Pusher furnace
Number of zones	five
Developed by	British Steel Corp.
Temperature accuracy of model	32°C

This paper describes development of a set of linear discrete time models for the slab temperatures. Inputs to the models are furnace temperature, pressure, combustion air flows and outputs are slab temperatures measured by thermocouples in the slab transport system. Due to the nonlinear nature of the PDE for the slab temperature it was necessary to define a set of operating conditions, each with a linear model of its own. The parameters of the linear models were identified using a least squares method combined with a statistical data analysis. The purpose of the model is to serve as a verification and back up for the slab temperature measurement devices.

[Veslocki, 1982]

Furnace type	Pusher furnace
Number of zones	5
Developed by	Inland Steel, USA
Temperature accuracy of model	±70°C

The article describes a 7 node 1D finite difference model for the slab temperature. The modeling also covers the furnace structure and the flame characteristics. A Thermophil system is used for measuring the slab temperature in three points in thickness direction when it is transported through the furnace.

[Wick, 1987]

Developed by	Hoesh Stahl AG, Germany

The subject is the construction of a nonlinear Kalman filter for estimating slab temperature. In the modeling the furnace is divided into 4 isothermal zones, where the gas temperatures are measured using thermocouples in the walls. The slabs are modeled as a continuous medium which moves with constant velocity through furnace. The slab temperature model includes top, bottom and mean temperature and includes heat transfer between gas and slab by radiation. The model is verified using simulations, where measurement noise is injected.

[Wick, 1990]

Developed by	Hoesh Stahl AG, Germany

The paper is based on [Wick, 1987] where a slab temperature predictor is developed using an extended Kalman filter. In the new paper the model is updated to include a pyrometer measurement of slab surface temperature. Again the algorithm is validated using simulations.

[Chapman *et al.*, 1991]

Furnace type	Pusher furnace
Developed by	Dept. of Mechanical Engineering, Kansas State University, USA

The article describes a model for furnace temperature where the slabs and furnace walls are modeled using 1D PDE's. The slabs are modeled as continuous media which moves with constant velocity through the furnace and the furnace chamber is modeled as a number of well-stirred zones. The model includes heat transfer by radiation and convection and investigates influence of

- Slab emmissitivity
- Combustion space
- Refractory emmissitivity

The conclusions are that high slab emmissitivity and little combustion space is most efficient. The emmissitivity of the refractory not of major importance. The article furthermore states that gas radiation is the most important factor of slab heating and gives a good basis for comparison of importance of gas and wall radiation and convection.

[Kusters and van Ditzhuijzen, 1994]

Furnace type	Walking beam furnace
Furnace capacity	300 ton/hour
Number of zones	7
Developed by	Dept. of Rolling Mills and Automation, Hoogovens, Holland
Temperature accuracy of model	±20°C

The article describes a linear multivariable model of a slab reheat furnace. The model includes heat generated due to combustion, convection between upper and lower zones and convection between upflow and downflow zones In the model the furnace is divided into five isothermal zones, with heat exchange between zones. The parameters of the model are found by system identification done using a black box approach with the multivariable ARX-method. The model is verified using measured data and good agreement is obtained.

[Barr, 1995]

Furnace type	Pusher furnace
Number of zones	5
Developed by	The Centre for Metallurgical Process Engineering, Vancouver, Canada
Implemented at	Inland Steel, USA
Temperature accuracy of model	±50°C

This article contains a detailed steady state modeling of an entire pusher furnace including slabs. The submodels describe

- Heat losses from furnace structure
- Heat conduction to slab transport system (skids)
- Energy transport from burners
- 2D modeling of slab temperature in width and thickness direction.

The heat input and output from the different models are aligned using the total energy balance for the furnace. The model is verified using data from Inland Steel, USA.

The model is designed to be general and it is used for analyzing the effect of different skid designs on the skid marks of the discharged slabs. It is concluded that the temperature gradient of the skid marks are in the interval of 130 – 200°C and that it is the skid design in the discharge end of the furnace which has the largest impact on the skid marks.

5.2 Furnace temperature control (level I)

[Hollander and Zuurbier, 1982]

Furnace type	Pusher furnace
Furnace capacity	99 tons/hour
Number of zones	3
Developed by	Hoogovens IJmuiden, Holland
Implemented at	Hoogovens IJmuiden, Holland
Reported fuel savings	8 %
Controller types:	PI-controller

In this article a level II open loop control scheme is described. The scheme has been developed using an off line mathematical model based on the 1D heat conduction equation with radiation from gas and refractory as boundary conditions. Radiation pyrometers are used for temperature measurement in the furnace. The system controls fuel quantity, air/fuel ratio and push rate directly. The fuel flow is controlled by PI-controllers, while the push rate is controlled using simplified expressions generated by the off line model. The zone temperature set points are generated using weighted temperature deviations of the measured slabs surface temperatures.

An analysis of control of a counterflow furnace is performed, and it is concluded that it has low energy consumption but is difficult to control due to the interaction between the control zones. One of the difficulties during delays is that only slabs near burners are heated properly, this is solved by injecting maximal amount of fuel when production starts after delay.

[Carpenter and Proctor, 1987]

Developed by	Rosemount Inc.

The article is a description of a distributed control system for level I furnace control. The air/fuel ratio control of the burners, the recuperator control, where two loops with controls flow through recuperator and a valve for cold air as protection is described. The furnace temperature control is based on thermocouple measurements in the furnace walls and the feedforward control strategy for the slab temperatures dependent on steel type and production rate also described. The control system also includes a delay strategy where the temperature lowered during delays and ramped back to normal set points when the production starts. The slab temperatures are controlled by a pyrometer surface temperature measurement in the furnace.

[McDonald, 1988]

Developed by	Italimpianti of America

This article contains a description of the advantages of using a distributed system for the level I control of reheat furnaces. The advantages of a distributed system are reported to be: it is redundant, has a good operator interface and is flexible. The system described in the article includes a table based feedforward control of the zone temperatures using material data and production rate, a delay strategy and an automatic or semi-automatic light up and shut down of the furnace. The burner control includes a variable air/fuel ratio depending on the flow through the burner, a variable combustion air pressure to save energy, and control of the flue gas temperature to prevent uneconomical furnace operation.

[Fadel, 1989]

Developed by	Leeds & Northrup Co, Pennsylvania, USA
Controller type:	PID-controller and extremal controller

The article contains a description of a distributed level I control system for handling control of key variables, material flow, and process surveillance. The advantages of the distributed system are better documentation, operator interface, and integration of the different tasks when controlling a reheat furnace. The system includes a self-tuning PID-controller and an extremal controller for controlling the air/fuel-ratio.

[Dunoyer *et al.*, 1997]

Furnace type	Batch furnace
Number of zones	1
Developed by	Control Theory & Applications Centre, Coventry University, UK
Implemented at	Swinden Technology Centre, British Steel, UK
Controller type:	PID-controller and bilinear self tuning controller

The furnace temperature of an experimental batch furnace is controlled using a bilinear self tuning controller. The performance of the nonlinear controller is compared to that of a conventional PID controller tuned to optimum performance. The experimental results show that the *integral of absolute error* for the bilinear self tuning controller is considerable lower than that of the PID-controller with the same fuel consumption as the PID-controller.

5.3 Slab temperature control (level II)

[H. E. Pike and Citron, 1970]

Furnace type	Pusher furnace
Number of zones	5
Developed by	General Electric Co. & Purdue University, Indiana, USA
Controller type	Optimal Controller

This article describes the design and simulation of an optimal controller for a reheating furnace with five control zones. The design is based on a nonlinear ODE for a slab heated only by radiation. First the optimal steady state furnace temperatures are found using an optimization package. Afterwards, the dynamic control problem is simulated where the load disturbance is a change of slab thickness. Using the optimization program a feed forward slab temperature control scheme dependent on production rate, slab thickness and disturbance location, is generated. The performance of the feed forward scheme is comparable to the performance of the optimal controller.

[Glatt and Macedo, 1977]

Furnace type	Pusher furnace
Developed by	British Steel Coorparation Battersea Laboratory, UK
Implemented at	Lackenby Works, UK
Reported fuel savings	20 %

This article is an early reference which gives a detailed description of installation of a level II furnace control system. The main motivation for installing the system is fuel savings. A simple version of the system had already been commissioned, and a more advanced system was under implementation when the article was written. The slab temperatures are measured using thermocouples in the furnace floor, and the simple system calculates the furnace temperature set points using a feedforward strategy. The advanced version of the system includes a slab temperature calculation, mill/furnace pacing, delay control and an adaptive slab temperature control strategy.

[Iwahashi *et al.*, 1982]

Furnace type	Pusher furnace
Furnace capacity	175 ton/hour
Number of zones	6
Developed by	Nippon Steel Corp., Japan
Implemented at	Nippon Steel Corp., Japan
Controller type:	Optimal controller

This paper describes the development of a Finite Element Model (FEM) and control algorithm for a level II slab temperature control system. The FEM model is able to calculate temperature profile in the thickness direction and skid marks and has the advantage of being more computational effective compared with a finite difference model. Based on the predictions from the FEM model the maximal heat input is as near the furnace discharge end as possible. Due to a limited computing capacity the temperature control is limited to a number of chosen "critical" slabs. The FEM model is verified using a more advanced off line model.

[Fontana *et al.*, 1983]

Furnace type	Walking beam
Furnace capacity	110 tons/hour
Developed by	Italimpianti S.p.A., Italy
Implemented at	Acciaierie de Piombino S.p.A, Italy
Reported fuel savings	5 to 10 %

The article describes a level II system for control of a billet reheat furnace. The system is based on a 2D model for the billet temperature distribution. In the model it is assumed that the slabs are heated by radiation from the top. The heating curves are found by off line simulations, and are functions of material data and production rate. The main idea in the slab temperature control is to move the center of heat input moved as close to the discharge side as possible since this yields the best utilization of the waste gases. The control functions of the system include direct control of the fuel flow rate, delay strategy, mill/furnace pacing, computation of heat balance for the furnace. The latter is used for testing the validity of the furnace measurements.

[Sultanian and Limbert, 1985]

Furnace type	Batch furnace
Number of zones	1
Developed by	Department of Mechanical and Aerospace Engineering, Arizona State University, USA
Controller type:	Optimal controller

This paper describes the development of an optimization algorithm for controlling the temperature of a batch furnace. A 3 point finite difference slab temperature model, combined with an ODE model for the furnace structure, and an integral equation for the scale formation are used as a basis for the optimization. The result of the optimization are furnace temperature trajectories that minimize scale formation and energy consumption, given a fixed heating time. The simulations indicate that a fuel saving of 10 – 20 % can be obtained by using the optimal trajectories.

[Klammer and Schupe, 1985]

Furnace type	Rotary hearth
Number of zones	9
Developed by	Mannesmannröhren-Werke AG, Germany
Implemented at	Mannesmannröhren-Werke AG, Germany
Reported fuel savings	10 %

The article features a very detailed description of a level II feedback slab temperature control system. The system is based on a 1D slab model with heating by radiation, which has been tuned using measurements from a test billet. Only one heating curve is used for all steel qualities.

[Roth *et al.*, 1986]

Furnace type	Pusher furnace
Furnace capacity	225 tons/hour
Developed by	UNISOR and IRSID, France
Implemented at	UNISOR Strip Mill, Dunkirk, France
Temperature accuracy of model	$\pm 18°C$
Reported fuel savings	7 %

This article gives a good description of a level II furnace control system. Five models are described

- A 1D slab heating model
- A rolling mill model for determining the temperature drop during rolling
- A fuel consumption model which is based on the heat balance for the furnace
- A 2D model for determining the skid marks, from which it is concluded that the shadow from the slab transport system is the dominating factor when forming the skid marks.
- A model for scale generation

The heating curves for minimizing fuel consumption are generated using the desired discharge temperature and the maximal permitted temperature gradient due to skid marks. The furnace temperature is chosen to be the lowest that ensures that all slab are heated to the specifications. A simplified version of the skid mark model is used for on line control. A pyrometer measurement of the slab surface temperature at the rouging mill is used for adaption of the temperature model. The system also includes furnace/mill pacing. The scale loss of the furnace is reported to be 1.05 %.

[**Leden, 1986**]

Developed by	MEFOS
Implemented at	Swedish Steel, Luleå, Sweden and others
Temperature accuracy of model	±50°C
Reported fuel savings	25%
Controller type:	PI-controller

The article starts with a short review of different methods for slab temperature control and then gives a detailed description of the feedforward/feedback scheme of the FOCS slab temperature control system. The feedforward part consist of feedforward tables for zone temperatures and the feedback part is based on the slab temperature calculation by the temperature predictor. The delay strategy of the level II system reduces furnace temperature using multipliers from table and the feedback block uses a PI-controller for each zone for controlling the slab temperatures. The furnace pacing is controlled by adjusting the drop out interval when too high furnace temperatures are encountered.

[**Schurko *et al.*, 1987**]

Developed by	Italimpianti of America
Reported fuel savings	8 to 15 %

This article gives a survey of the different level II slab temperature control algorithms

- **Feedforward control.** the systems are stated to be easy to implement but can only handle steady state operation. Generally the slab temperatures are unknown when the furnace is controlled by this type of systems.
- **Control by pyrometer measurements.** Slab temperature measurement in rolling line yields too large time delays and it is therefore necessary to measure the slab temperature in the furnaces. Since it is only possible to measure the surface temperature it is not easy to determine the mean slab temperature and the temperature gradients.
- **Model based slab temperature control,** this is said to be the best solution. Using this method the steel temperature can be controlled directly and delays can be handled by changing the steel temperature and not the furnace temperature.

The authors also emphasize that the whole plant should be considered when choosing the furnace automation system and not only the furnace.

[**Anon, 1987**]

Developed by	Misubishi Electric Corporation, Japan
Temperature accuracy of model	±15°C
Reported fuel savings	10 %

The article gives a brief description of a billet temperature control system. The system is based on a finite difference billet temperature model where the furnace and billet temperatures are determined using the fuel flows.

[Yang and Lu, 1988]

Furnace type	Pusher
Developed by	Laboratory for Industrial Process Modeling and Control, Zehjiang University, China
Reported fuel savings	9 %
Controller type:	Optimal controller

The article describes a level II feedback system for controlling the slab temperature. The slab temperature model is a 1D PDE, but unlike other references it is assumed that the heating is done by convection only. The PDE model is discretized using the finite difference method. The optimal zone temperatures are generated on-line on the basis of the linear discrete model and a set of heuristic rules. One of the main objectives of the optimization is the reduction of fuel consumption. This is achieved by moving the center of heat input as far as possible from the gas output. It is reported that the system has been controlling on three pusher furnaces for a one year period.

[Garcia *et al.*, 1989]

Furnace type	Walking beam
Furnace capacity	300 tons/hour
Number of zones	8
Developed by	Dept of Electrical Engineering, Oviedo, Spain
Controller type:	Optimal controller

The paper describes the development of a simulator, an on-line model, and a control strategy for two identical furnaces at the Ensidesa hot strip mill in Avilès, Spain. The two temperature predictors are described as a complicated off line model and a simple on line model which appears to be a 2 point finite difference model with heat transfer by gas and wall radiation. The control strategy controls the slab temperature using values from the model and feedback from the pyrometer measurements. The energy consumption is minimized by moving the heat input as near the furnace discharge end as possible. The furnace temperatures are determined using an optimization algorithm that also uses a model based feedforward from previous furnace zones.

[Pichler and Langer, 1989]

Furnace type	Pusher furnace
Developed by	Voerst-Alpine Stal, Austria
Implemented at	Voerst-Alpine Stal, Austria
Temperature accuracy of model	±22.5°C
Reported fuel savings	3.5 %
Controller type:	P-controller

The article contains a description of a level II feedback slab temperature control system. The system is based on a 1D PDE model with heat transfer due to radiation and convection form the furnace walls and gas. The slab temperature model is tuned using slab temperature measurements. The slab temperatures weighted within a furnace control zone are controlled using a P-controller. The heating curves are functions of production rate and material parameters, and have been determined by the skid marks dependent on the different operation conditions. The system has pacing like functions and automatic delay handling.

[Halliday, 1990]

Furnace type	Pusher furnace
Furnace capacity	10 to 300 tons/hour
Developed by	Laidlaw Drew Ltd., Scotland, UK
Implemented at	Several British Steel Mills
Temperature accuracy of model	±1 %
Reported fuel savings	10 to 16 %

The article gives a brief description of a level II feedback temperature control system. The temperature control is based on model developed by W. T. Kodz in 1966. This model has been tuned from measurements from a large number of reheat furnaces. The article states that the slab heating is done mainly by radiation from the furnace walls and roof and the temperature calculation is based on thermocouples placed in the furnace walls and roof. The delay strategy of the system is as follows: temperature set points lowered during stops, when the rolling mill resumes production the furnace temperatures are increased to the maximal permissible level.

[Hutchison and Passano, 1990]

Furnace type	Pusher furnace
Furnace capacity	125 tons/hour
Number of zones	3
Developed by	Salem Automation, USA
Implemented at	Conshohocken Plant, Luken Steel Co., USA
Temperature accuracy of model	±27°C
Reported fuel savings	19 %

The article describes the implementation of a level II slab temperature feedback control system. The system is based on an 1D PDE slab model with heating by radiation, conduction and convection as boundary conditions. The system also features a pacing function coordinating the production rate with the rest of the rolling line. The delay strategy is based on slab temperature which makes it possible to optimize the slab temperatures also during delays.

[Yoshitani *et al.*, 1991]

Furnace type	Pusher furnace
Developed by	Nippon Steel Corporation
Reported fuel savings	11 % (simulated)
Controller type:	Generalized Predictive Controller

This paper describes the design of a level II slab temperature control system where the furnace is charged with a mixture of hot slabs directly from the steel works and cold slabs from the stock. First two models are developed

- A nonlinear PDE model with heating by radiation for simulating the slab heating
- A linear ODE for controlling the slab temperature. The linear model is a non minimum phase system.

Input to both models are the fuel flows. The heating curves for the slab temperature control are found by an on line optimization of the furnace operation using the nonlinear model. With the heating curve as reference the slab temperatures are controlled using a Generalized Predictive Controller, which is designed using the linear model. It is reported that the control law will be implemented using transputer technology.

[Yang *et al.*, 1991]

Developed by	Research Institute of Industrial Control, Zhejiang University, China
Controller type:	Optimal controller

The paper describes a system for Computer Aided Design of furnace control strategies based on traditional control theory and Artificial Intelligence techniques. The system is based on a discrete mathematical model for simulating the slab temperature. The model has been verified using real world data from several sites. Using the model it is possible to develop furnace control strategies and gain knowledge about the reheating process. The system includes an optimization routine for automatic generating of feedforward schemes for controlling the slab temperature and minimizing the energy consumption. It is stated that feedforward schemes are under implementation in several places

[Rixin and Baolin, 1992]

Furnace type	Pusher furnace
Number of zones	3
Developed by	Department of Metallurgy, Kunmin Institute of Technology, China
Temperature accuracy of model	$\pm 15°C$
Controller type:	Optimal controller

The article describes a model based level II feedback slab temperature control system. The system is based on the usual 1D slab heating model with heating by radiation. The model is tuned using data from QiQiHear Steel Works. The furnace temperature set points are found by minimizing the slab enthalpy as a function of time. A similar strategy is used during delays. The claimed temperature accuracy is found using simulations.

6. Conclusions

This report contains an introduction to classical and present furnace control. To give a basic understanding of the control problem a description of the reheat furnace no. 2 at The Danish Steel Works Ltd is first given. After this, the slab heating process is analyzed and analytical models for the mean temperature and temperature distribution are described. The analysis shows that there is a conflict between obtaining a large furnace capacity on one side and having low energy consumption and small temperature gradients on the other side. These results show why it is worthwhile to use advanced model based control strategies for controlling the reheat furnaces.

After the analysis of the heating process, the state of the art furnace control systems is described. Since it is not possible to measure the slab temperature, prediction models are used when controlling this variable. The set points for the furnace temperatures are generated based on the estimated slab temperatures. Among other difficulties the furnace temperature is used for controlling several slab temperatures. This makes a careful choice of the furnace temperature necessary. Other functions of the slab temperature control systems are special strategies for production delays and pacing systems for coordination between furnace and rolling mill operation.

In the literature review, short resumes of 31 papers and journal articles are given. The key figures show that it is possible to obtain slab temperatures within an accuracy of $\pm 50°C$ and energy saving of 5% to 20%. This gives another explanation for the success of the model based level II slab temperature control systems. The current tendency of the work on slab temperature control seems to go in the direction of pacing systems and more advanced modeling and control of the reheating process.

The importance of the prediction of the slab temperature is seen from the fact that the models normally are used only for temperature prediction. Very few examples of controller designs based on the slab temperature models have been found in the literature. The most common solution for determining the furnace temperature set points are optimization algorithms using the prediction models and PI-controllers. It is also remarkable that only two references on system identification have been found. No other reports on parameter estimation of the rather complex models are given.

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