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Adaptive Supervisory Control of an Industrial Steel Slab Reheating Furnace

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Abstract

A novel supervisory control system was developed for a boutique, walking beam-type, natural gas-fired industrial reheating furnace for steel slabs. The control system was developed to provide furnace temperature set points for the operators. The system development ideology was to utilise the considerable and inexpensive computing resources available today, to solve problems in real time in a discrete and digitised manner in place of complex analytical solutions. The control system utilises an entirely iterative regime to calculate the required furnace heating profiles to ensure that slab delivery temperatures are optimised. A two-dimensional slab conduction and radiation model was developed to fulfil the supervisory control function. The results are promising with estimated control performance at least as good as current manual achievement but with the benefit of additional information being provided to the expert human operator in the control loop.

KEYWORDS: adaptive supervisory control, steel slab, reheating furnace

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1. INTRODUCTION

A reheating furnace is a key process unit of a strip mill in a steel plant where slabs are heated to have uniform target temperatures. Since slab heating requires lots of energy, it is desired that energy can be saved by controlling the temperatures of the discharged slabs to be heated as closely as possible to the target temperature.

Slab temperature after rolling at a roughing mill is called as rougher delivery temperature (RDT). It is the key indicator used by the furnace operators to determine adequacy of heating. It gives an indication of the slab temperature on entry to the hot rolling line and is the parameter specified for the heating of each slab. Operators judge the RDT based on the time the slab has been in the furnace, the furnace temperature profile the slab has been exposed to and the slab surface temperature before it is discharged. It is essential that the RDT is the crucial parameter for the control system to aim for. A RDT that is too high signifies a waste of gas and unnecessary time spent in the furnace, a RDT that is too low causes excess wear on rolling equipment. Comparing the RDT requested to that actually reached by the operators, we notice that the actual RDTs are consistently higher 24.5 ˚C than what is required. This provides a great opportunity to save energy and improve the quality.

Reheating furnace control has been addressed previously by many researchers. Key studies include: multivariate control to replace PID control in zone temperature control (Rohal *et* al. 1994), improved self tuning bilinear control for zone temperature control (Dunoyer *et* al., 1997), non-linear control based on the ideal slab heating curve (Pedersen and Wittenmark, 1998), multiple models used to control zone temperatures (Zhang *et* al. 2002), supervisory control based on the differential equations with measured boundary conditions (Wang *et* al., 2003) and the neural network models (Kim *et* al., 1998) etc..

In large scale operations a reheating furnace will typically heat one product to one temperature, continuously, for a long period of time before switching to another product. This essentially leads to a steady state situation which is predictable and readily controlled. Previous studies have focussed on these furnaces.

The reheating furnace at New Zealand Steel is the walk beam furnace, the slab move on top of rails that convey them forwards and do not allow them to touch each other. The furnace is termed "boutique". At any time there will be several grades of steel consisting of different dimensions and with different temperature requirements. They will be scheduled for heating in the optimal order for a downstream process. Unfortunately, this is an order which has little regard for an optimal furnace operation. Because of above reasons, a supervisory control regime will be the optimal control strategy for New Zealand Steel.

The supervisory control problem of a reheating furnace can be summarized as follows: given a slab type and the slab target temperature, each zone temperature of a reheating furnace is determined in an optimal manner. This procedure requires a model to predict the temperature profile of a slab. Since the operation of the reheating furnace studied in this paper are limited by its physical nature, mathematical models (of fixed slab conduction and the net radiation energy absorbed models), are developed. It is based on the models developed by Ezure *et* al. (1997), Pedersen and Wittenmark (1998), Zhang *et* al. (2002) and Wang *et* al. (2003). For this reheating furnace, the slab temperature profile is not directly used for judging the adequacy of the slab heating; instead the RDT is used as the key indicator. The relationship between the slab temperature profile and the RDT is established. Based on this relationship, a novel supervisory control system was developed.

The outline of this paper is as follows: In the following section the structure of the furnace and its characteristics are introduced. In the next section a nonlinear model for the temperature profiles of the slabs in the furnace zone is constructed. This model is used for analysis and determination of the furnace zone temperatures. The development of the adaptive supervisory control for a reheating furnace is discussed in the subsequent section. The paper concludes with a summary of the key results of the proposed methodology and the future research in the final section.

2. REHEATING FURNACE

Reheating Furnace

The reheating furnace at New Zealand Steel's Hot Strip Mill is a walking beam type and is natural gas fired. It uses 1000 gigajoules of gas energy per year. The furnace is divided into six distinct and individually controllable zones, each separated with partial walls which effectively block radiation transfer and hinder convective transfer. The zones are referred to as preheat, heating and soak zones, each with upper and lower components. The preheat zone has 10 burners, the heating zone has 12 burners and the soak zone has 12 burners. The preheat zone has a heating capacity of 35.61 megawatts, the heat zone has a capacity of 27.11 megawatts and the soak zone has a capacity of 12.17 megawatts.

Furnace and Slab Temperature Measurement

The furnace uses six Land Systems pyrometers to measure the slab surface temperature at either end of the slab in three positions in the furnace. The pyrometers are positioned near the end of preheat, heat and soak zones and only measure the temperatures of the top surfaces of the slabs.

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The furnace has 24 thermocouples, eight in each zone. The thermocouples measure the furnace temperature on the roof at the sides near the bottom of the furnace. The thermocouples are positioned on both sides of the furnace and at each end of each zone such that each zone has a thermocouple in every corner.

Control System

The furnace actuators are directly controlled by a bank of programmable logic controllers (PLC's). The PLC's take temperature set points and control the fuel and air flows to meet the temperature requirements using proportional, integral and ratio control to ensure that gas and air flows remain in a safe ratio to each other. The furnace is manually operated by the operators who choose the temperature set points for each zone, decide what pace rate to move the slabs and when a slab is ready for discharge.

3. MODEL DEVELOPMENT

3.1. Slab Temperature Models

A slab's internal temperature is far more important than the external temperature for determining its RDT (Laurinen and Roning, 2005). The RDT is an important indicator determining when a slab is ready to discharge. Under the current manual system operators must err on the side of caution to ensure the core temperature is high enough. A calculated multidimensional slab temperature profile would allow calculation of the expected rougher delivery temperature and prevent the gas and time waste associated with waiting to ensure adequate core temperature.

Based on Fourier's Law (e.g. Perry *et* al., 1997), the conduction through a slab can be modelled as:

$$\frac{dQ}{d\theta} = -kA\frac{dT}{dx} \tag{1}$$

where Q is energy transferred measured in Joules, θ is time measured in seconds, k is the thermal conductivity of the material measured in J/msK, A is the area perpendicular to the direction of conduction measured in m^2. T is the temperature at position x in the material in degrees Kelvin and x is distance through the material in metres.

The solution of Eq. (1) is more complex than steady state condition; the general numerical method developed by Dusinberre (1949) is employed in this paper. The slab is divided into 72 sections Figure 1(a)) in two dimensions (72 sections were chosen as this provides a good balance of resolution and performance, on a faster computer system more sections could be used). Users define the time step, Δθ, and slice thickness, Δx, so that the slab temperature profile can be estimated. For example, to calculate the temperature of the centre section 5 in a case of five adjacent sections shown in Figure 1(b), the new temperature of section 5 at time (nθ + Δθ) can be obtained with the specific steel heat capacity Cp and density ρ as follows, (Eq. 2 and 3).

$$T_5(n\theta+\Delta\theta)=T_5(n\theta)+\frac{\Delta\theta k}{C_p\rho}\left(\frac{T_5(n\theta)-T_2(n\theta)}{D^2}+\frac{T_5(n\theta)-T_4(n\theta)}{L^2}+\frac{T_5(n\theta)-T_6(n\theta)}{L^2}+\frac{T_5(n\theta)-T_8(n\theta)}{D^2}\right) \quad (2)$$

and the new temperature of section two at time (nθ + Δθ) can be found as:

$$T_2(n\theta+\Delta\theta)=T_5(n\theta)+\frac{Q_{Radiation}(n\theta)}{C_p\rho DL}+\frac{\Delta\theta k}{C_p\rho}\left(\frac{T_2(n\theta)-T_1(n\theta)}{L^2}+\frac{T_2(n\theta)-T_5(n\theta)}{L^2}+\frac{T_5(n\theta)-T_3(n\theta)}{D^2}\right) \quad (3)$$

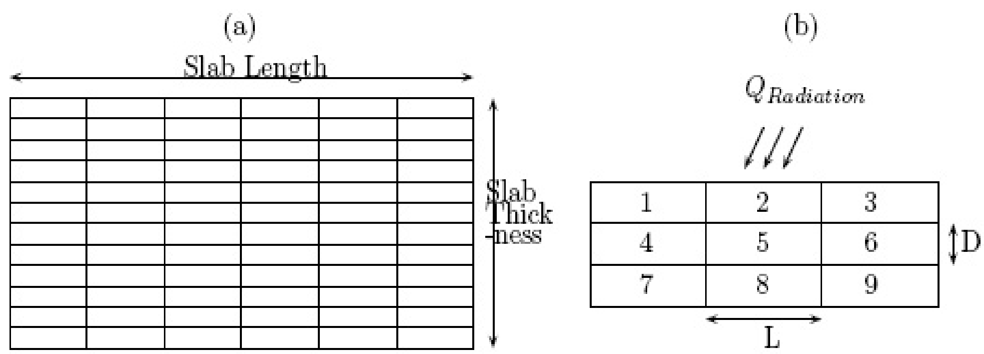

Figure 1: Slab sections: (a) cross section of slab temperature zones (b) enlargement of nine adjacent temperature zones

In order to estimate the temperature profile of each section, the heat flux to the six top and six bottom sections of a slab must be determined. There are two modes of heat transfer involved in heating a slab in the furnace: convection and radiation. For the furnace operates at temperatures in excess of 1000 ˚C, since the

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radiation energy transfer is proportional to the fourth power of temperature, the radiant heat transfer dominates the slab heat transfer (Mullinger, 2005). For our study, the convection heat transfer will be ignored and absorbed into adaptive coefficients, especially on the scales of accuracy required for the specific application of a reheating furnace.

To accurately calculate the radiation energy exchange at a point it is necessary to consider the hemisphere of flux "seen" by that point (Jenkins, 2005). This is determined by the hemisphere of temperatures and emissivity "seen" by the point as illustrated in Figure 2.

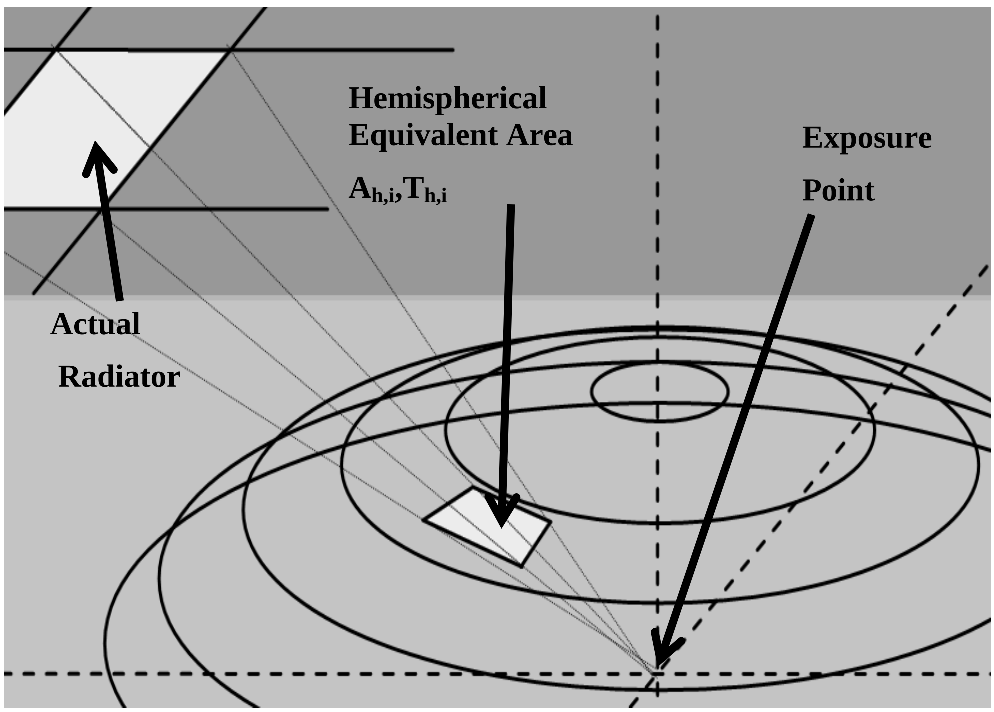

Figure 2: Radiation exposure at a point

To calculate the radiation flux "seen" by each surface section on a slab, the following procedure was applied. A mathematical model for the furnace geometry was developed. This model is divided into one metre grids and their centre temperatures are calculated by linearly interpolating between thermocouple readings. Faster computers would readily be able to process a smaller grid section. The slab radiation exposure is determined by interpolating between twenty four thermocouples embedded in the furnace surfaces and then calculating the hemispherical equivalent of the radiating surfaces in line of sight to a section of the slab. The radiation energy $Q_{Radiation}\ (n\theta)$ in Eq. (2) can be calculated as:

$$Q_{Radiation}(n\theta) = \sigma A\left(\alpha_{slab}\varepsilon_{refractory}\frac{\sum\left(A_{h,i}T_{h,i}^{4}(n\theta)\right)}{A_{h,i}} - \varepsilon_{slab}T_{2}^{4}(n\theta)\right) \tag{4}$$

where σ is the Stefan-Boltzmann constant, α is the absorptivity of a grey body and ε is the emissivity of a grey body.

Boundary condition and assumptions

The heat flux to the slabs is determined by means of furnace temperature and heat transfer coefficients such as slab surface absorptivity and furnace refractory emissivity.

24 thermocouple temperature sensors are used to build up a temperature profile for the roof and walls of the furnace. The temperature at a specific point on the furnace interior is based on a linear extrapolation from the nearest four thermocouples.

The actual radiation absorbed by the slab is a function of the slab surface emissivity, slab surface absorptivity and the furnace refractory emissivity (Perry et al., 1997). The refractory absorptivity is neglected as it is assumed they will be maintained at approximately constant temperature by the zone control system. The emissivity and absorptivity are ratios of the energy which would be absorbed or emitted by a black body (perfect radiator). The slab and refractory absorptivity and emissivity are calculated based on a function of experimentally determined coefficients and surface temperature (Jenkins, 2005 and Mullinger, 2005).

The walking beam, which the slabs rest on, is both insulated and water cooled. The degree of insulation is a trade off between the radiation shadow that insulating material casts on the slab and the greater heat lost to the water cooling if less insulation is applied. Conduction losses to the walking beam cooling system are not negligible and result in cold areas (commonly called skid marks) forming in the heat profile of the slab (Ezure et al., 1997). The effects of the water cooled walking beam are not directly accounted for in the model but are accounted for by the variable adaptive coefficients affecting radiation transfer in the model. The coefficients are continuously revised based on measured data and are designed to keep the model in close correlation with the physical system.

Figure 3 shows a selection of heating profiles taken form a simulation run using real data. It indicates that the slab models can provide reliable slab temperatures.

The slab modelling system is adaptive. It applies the learned coefficients such as the absorptivity and emissivity coefficients of slabs as they are processed. When a slab enters the furnace its temperature profile is calculated according to

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the aforementioned slab temperature models. In addition to the calculations for absorbed radiation, there is a coefficient applied for each slab. This coefficient will be referred to as the prediction coefficient. The prediction coefficient is applied to the slab's absorptivity value during calculation of the radiation absorbed. The prediction coefficients are stored for each grade of steel and for each heating zone. They are updated as each slab progresses through the furnace. The initial value of the prediction coefficient applied to a slab is the average value of previous slabs of the same grade which have been through the furnace. These prediction coefficients form the basis of the adaptive prediction system.

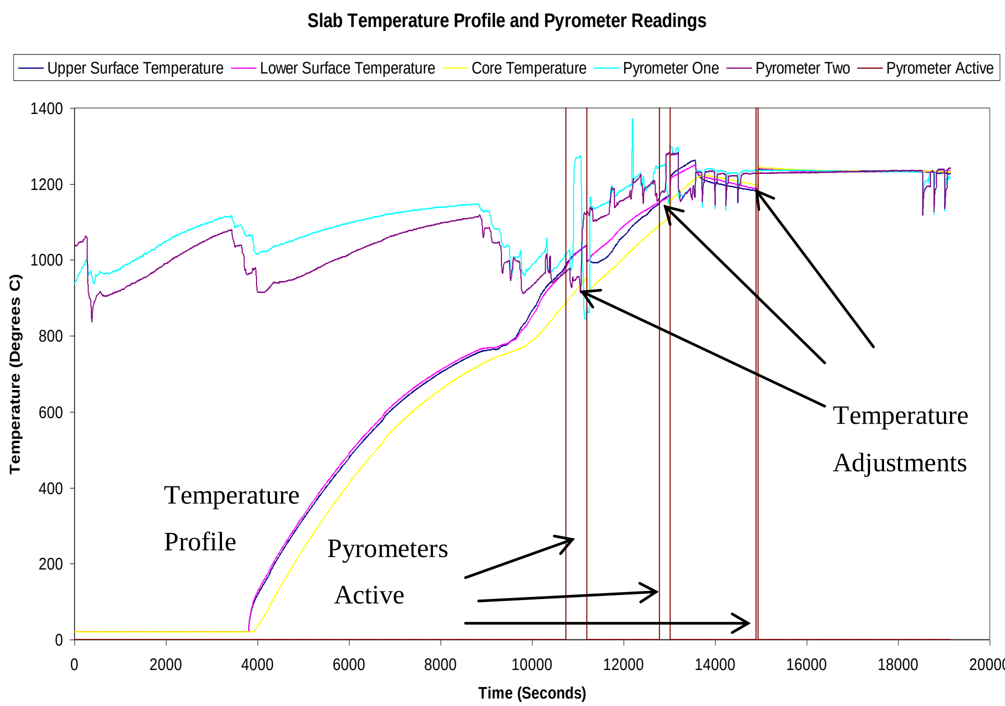

Figure 3: Slab temperature profile and pyrometer readings

3.2. Rougher Delivery Temperature

Further analysis of the data reveals some consistencies which can be used to predict rougher delivery temperature. The difference between the RDT and the calculated mean slab temperature used the slab models for 94 samples confirms that the data is approximately normally distributed with a median of 184 ˚C and an inter-quartile range of 51 ˚C. This means that predictions based on subtracting 184 ˚C from the mean slab temperature will result in a RDT which is within 25.5

˚C of the actual value, 50% of the time. Whilst not ideal, the variation is similar to what the operators currently achieve.

4. CONTROL DEVELOPMENT

A supervisory control system to obtain the furnace temperature setpoints was developed. The control system was designed to optimise the furnace time-temperature profile so that steel slabs are delivered as close as possible to their target delivery temperatures. The primary control philosophy used by the new supervisory control system was to do most of the heating in preheat and heating zones and then fine tune in the soak zone.

4.1. Control Strategy

This supervisory control system is summarized in Figure 4. The aim of the control system is to generate a temperature profile for each zone which will result in the average slab being delivered as close as possible to its aim delivery temperature. However, this control solution will inevitably mean that some slabs will be delivered too hot and some too cold.

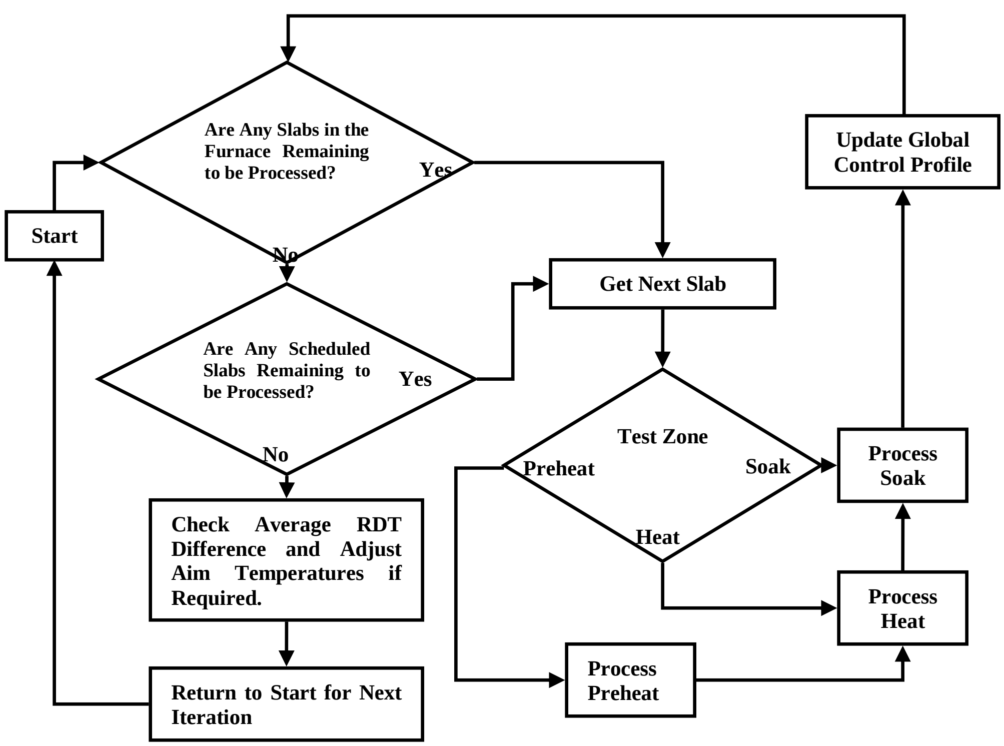

Figure 4: Flow chart of a supervisory control of the furnace temperature

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The control system scans through all of the slabs currently loaded in the furnace. It determines which zone each slab is in and sends it to be processed by the relevant zone processor. When every slab in the furnace has been processed the control system then processes the next six slabs in the schedule. Six was chosen as it is the minimum number of slabs needed to ensure the furnace is kept full up until the end of the control simulations. The required furnace temperature profile for each slab will be calculated. A trial is run with the slab moving through the preheat, heat and soak zones whilst all three zones are set to decrease temperature at the maximum permitted rate down to their minimum allowed temperature. The slab's rougher delivery temperature (RDT) at discharge is calculated. If the calculated rougher delivery temperature is sufficient then that heat control profile is used. The individual slab control profile is then merged with the global control system in Figure 4.

4.2. Updating the Control Profile

The control profile is always changing as the various slabs update it for their requirements. For example, consider the following hypothetical situation.

One slab has particularly high heating requirements and so demands that the soak zone temperature stay high for longer than an upcoming slab requires. The upcoming slab realises that it is going to receive more heat than it needs in the soak zone and so calls for the temperature in the prior (heating) zone to be reduced for the period after the slab with the high temperature requirements has left the heating zone and before it leaves the heating zone. Of course it is quite likely that another slab following the cooler slab has higher heating requirements and countermands to the effect that the heating zone also run at a high temperature. This inevitably results in the slab with the lower temperature requirements being overheated. So long as the furnace average deviation from desired delivery temperature is kept in check this is accepted as necessary.

4.3. Monitoring Average Deviation

Checking the average deviation from desired RDT is an important overriding principle of the control system. For all slabs in the furnace, this deviation must always be within ten degrees Kelvin.

The control system is designed such that even through every individual slab is aiming for delivery at temperature; the slabs which require higher furnace temperature take priority. A slab can never reduce the temperature profile unless either it increased it or it has been released for reducing by another slab which previously increased it. This leads to the potential for a small number of slabs with unusually high heating requirements to cause all the other slabs to overheat.

To compensate for this the average delivery deviation is checked. If it is found to be outside of the accepted limits then the rouge slabs (which are causing the furnace to run too hot for the other slabs) have their aim delivery temperatures artificially reduced by as much as 20 degrees or until the delivery temperature is back within limits. In theory this will cause the rouge slabs to be delivered below temperature.

In reality slabs which demand such high heating requirements are often erroneously doing so. Typically this only happens until the adaptive control system has processed enough slabs of this grade to have a valid table of coefficients for the grade. Another cause could be the scheduling of a long period of high speed running with no delays. Given the rarity of such a schedule being followed without any delays it was decided that it was best to risk the possibility of the slabs being delivered slightly below temperature for the betterment of the average slab. It should also be noted that adjustments made fall well within the possible margins of error for delivery temperature and so may result in accurate delivery temperatures regardless.

4.4. Pace Scheduling

In order for the control system to calculate future temperature profiles, the control system needs to know the future location of the slabs. This is calculated from future pace rates of the furnace. These can be set for any period in the future. A delay would be represented by setting a pace rate of zero.

4.5. Zone Saturation

If for some reason a slab spends an extended period of time in one zone (such as during a delay), it is possible that the slab will reach saturation and its temperature profile will become homogenous. The control system needs to be aware of this condition so that it does not try in vain to heat the slab further in that zone.

4.6. Simulation

The proposed slab model and supervisory control algorithm were implemented for the simulated process, and the results are listed in Figure 5. It is shown that the RDT outputs from the simulation using the developed supervisory control system. The circled columns show the calculated RDT and required RDT respectively.

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Note that the average deviation is close to ten degrees Kelvin for the slabs being processed. This is within the allowable limits for the furnace.

```
processallslabs called
error handler OFF
had to reset sample time
PREHEAT FINAL RDT DATA IS 1021.3 1020        658151020 0 1 1020
PREHEAT FINAL RDT DATA IS 1036.75 1050        658158040 327 1 1050
PREHEAT FINAL RDT DATA IS 1031.99 1020               658248060 100 1 1020
PREHEAT FINAL RDT DATA IS 1023.62 1020               658264020 100 1 1020
PREHEAT FINAL RDT DATA IS 1017.33 1020               658244020 100 1 1020
PREHEAT FINAL RDT DATA IS 1022.7 1020               657882750 117 1 1020
PREHEAT FINAL RDT DATA IS 1017.84 1020               658217060 100 1 1020
PROFILE UPDATED
Average RDT Delta is -5.97367
Now copying global heating profile to file for test
PREHEAT FINAL RDT DATA IS 1024.69 1020      658151020 0 1 1020
PREHEAT FINAL RDT DATA IS 1027.35 1050      658158040 327 1 1050
PREHEAT FINAL RDT DATA IS 1030.43 1020             658248060 100 1 1020
PREHEAT FINAL RDT DATA IS 1023.08 1020             658264020 100 1 1020
PREHEAT FINAL RDT DATA IS 1017.42 1020             658244020 100 1 1020
PREHEAT FINAL RDT DATA IS 1022.82 1020             657882750 117 1 1020
PREHEAT FINAL RDT DATA IS 1017.97 1020             658217060 100 1 1020
PROFILE UPDATED
Average RDT Delta is -8.98114
Now copying global heating profile to file for test
PREHEAT FINAL RDT DATA IS 1024.67 1020      658151020 0 1 1020
PREHEAT FINAL RDT DATA IS 1036.05 1050      658158040 327 1 1050
PREHEAT FINAL RDT DATA IS 1032.1 1020             658248060 100 1 1020
PREHEAT FINAL RDT DATA IS 1023.65 1020             658264020 100 1 1020
PREHEAT FINAL RDT DATA IS 1017.46 1020             658244020 100 1 1020
PREHEAT FINAL RDT DATA IS 1022.76 1020             657882750 117 1 1020
PREHEAT FINAL RDT DATA IS 1017.98 1020             658217060 100 1 1020
PROFILE UPDATED
Average RDT Delta is -4.64069
```

Figure 5: RDT outputs based on the simulation using a developed supervisor control system

5. CONCLUSIONS

Most of the literature reviewed has focused on developing control systems where a temporary steady state solution is attainable. This is not the case at New Zealand Steel and so complicates the control problem.

Radiation and slab heating models have been developed. They are adaptive and steel grade specific. The model has been validated and appears to perform well. The relationship between the RDT and the discharged slab temperature profile has been established. A supervisory control system has been developed to improve the furnace temperature performance and the slab heating quality. The RDTs from the control system appear to be valid as they correlate well with on line operation.

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