A Transient, Three-Dimensional, Thermal Model
Of a Billet Reheating Furnace

by

Kenneth Erwin Scholey
B.A.Sc., The University of British Columbia, 1988
M.A.Sc., The University of British Columbia, 1991

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Department of **Metals and Materials Engineering**

The University of British Columbia
Vancouver, Canada

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Abstract

Situated between the casting and rolling operations, the reheating process ensures steel billets or slabs are at temperatures high enough (~1200°C) to enable subsequent deformation processes to be carried out economically. Industrial reheating furnaces have varying designs, utilize different fuel mixtures and employ top, side or bottom firing. Under steady-state operating conditions, the challenge is to achieve good temperature homogenization while minimizing fuel consumption and maximizing furnace throughput. During furnace stoppages, which are caused by delays in the rolling mill, there is a need to minimize fuel consumption and maintain discharge temperatures.

To gain better insight into the operation of a billet reheating furnace, a transient, three-dimensional thermal model has been developed. Radiative heat transfer in three-dimensions is solved using Hottel's "Zone Method", employing a clear-plus-three-grey gas model to represent the furnace atmosphere. In this method, the geometrical aspects of the problem are treated separately to produce total exchange areas that can be stored for repeated use. The main module then calculates the energy released through combustion, the heat transferred to the steel and the movement of the charge during each time step. Gas temperatures are determined from energy balances using a Newton-Raphson iterative technique. Conduction in the billets is solved in three-dimensions by taking into account heat transfer in the gaps between and underneath the billets. The model further evaluates heat losses through the furnace roof, walls and hearth.

The mathematical model was verified using industrial data obtained from plant trials conducted at two Canadian steel mini-mills. Results from the plant trials indicated that the billets continued to increase in temperature during furnace stoppages. The model suggests that this is due to continuous burner firing during these stoppages even with lower firing levels. For one of the furnaces, the model predicts the thermal efficiency to be 31% for the heating of 0.15 m (6") billets, with 68% of the combustion energy lost in the flue gases and the remainder lost through the refractory. Improved performance could be realized through better control of the furnace atmosphere, with the air/fuel ratios maintained at levels closer to stoichiometric, as well as the installa-
tion of a recuperator to preheat the combustion air.

Different delay firing strategies that focussed on the recovery of the furnace were exam-
ined with the model and it was found that the sequential return to steady-state firing reduces the
extent of billet over-heating while ensuring newly charged billets reached adequate rolling tem-
peratures. The model was also used to examine the effect of air/fuel ratios in each of the furnace
control zones and the benefits of recuperatively preheating the combustion air or hot-charging,
where the billets are charged into the furnace soon after casting.
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Nomenclature

\( a_\alpha \)  
\begin{align*}  
\text{gas absorptivity coefficient (} & \text{-}\text{)} 
\end{align*}

\( a_\varepsilon \)  
\begin{align*}  
\text{gas emissivity coefficient (} & \text{-}\text{)} 
\end{align*}

\( A \)  
\begin{align*}  
\text{area (} & \text{m}^2\text{)} 
\end{align*}

\( \Delta A' \)  
\begin{align*}  
\text{incremental area of surface } A \text{ (} & \text{m}^2\text{)} 
\end{align*}

\( b_\varepsilon \)  
\begin{align*}  
\text{weight used to calculate gas emissivity coefficient (} & \text{-}\text{)} 
\end{align*}

\( c_\alpha \)  
\begin{align*}  
\text{weight used to calculate gas absorptivity coefficient (} & \text{-}\text{)} 
\end{align*}

\( C_p \)  
\begin{align*}  
\text{specific heat (J/kg}^{-}\text{°C)} 
\end{align*}

\( D \)  
\begin{align*}  
\text{diffusion coefficient (cm}^2\text{/s)} 
\end{align*}

\( E \)  
\begin{align*}  
\text{radiative emissive power from a black body (W/m}^2\text{)} 
\end{align*}

\( g \)  
\begin{align*}  
\text{gravitational acceleration (} & \text{m}^2\text{/s)} 
\end{align*}

\( gg \)  
\begin{align*}  
\text{gas-gas direct exchange area (} & \text{m}^2\text{)} 
\end{align*}

\( \overline{GG} \)  
\begin{align*}  
\text{gas-gas total exchange area (} & \text{m}^2\text{)} 
\end{align*}

\( \overline{GG}^\prime \)  
\begin{align*}  
\text{gas-gas directed exchange area (} & \text{m}^2\text{)} 
\end{align*}

\( h \)  
\begin{align*}  
\text{heat transfer coefficient (W/m}^2\text{-K)} 
\end{align*}

\( k \)  
\begin{align*}  
\text{thermal conductivity (W/m}^{-}\text{°C)} 
\end{align*}

\( k_i \)  
\begin{align*}  
\text{extinction coefficient of the } i\text{'th grey gas (atm}^{-1}\text{m}^{-1}\text{)} 
\end{align*}

\( K \)  
\begin{align*}  
\text{product of extinction coefficient, } k_i \text{, and partial pressure, } p \text{. (m}^{-1}\text{)} 
\end{align*}

\( K \)  
\begin{align*}  
\text{orifice plate flow coefficient (} & \text{m}^2\text{)} 
\end{align*}

\( l \)  
\begin{align*}  
\text{path length (m)} 
\end{align*}

\( MW \)  
\begin{align*}  
\text{molecular weight (g/mole)} 
\end{align*}

\( N \)  
\begin{align*}  
\text{number of elements (-)} 
\end{align*}

\( Nu \)  
\begin{align*}  
\text{Nusselt number (-)} 
\end{align*}

\( p \)  
\begin{align*}  
\text{partial pressure (atm)} 
\end{align*}

\( P_{\text{total}} \)  
\begin{align*}  
\text{total pressure (atm)} 
\end{align*}

\( Pr \)  
\begin{align*}  
\text{Prandtl number (-)} 
\end{align*}

\( q \)  
\begin{align*}  
\text{heat flow (W) or heat flux (W/m}^2\text{)} 
\end{align*}

\( Q \)  
\begin{align*}  
\text{gas flow rate (m}^3\text{/h)} 
\end{align*}

\( r \)  
\begin{align*}  
\text{distance between zone elements (m)} 
\end{align*}

\( R \)  
\begin{align*}  
\text{universal gas constant (8.314 atm m}^3\text{/g-mole °C)} 
\end{align*}

\( Re \)  
\begin{align*}  
\text{Reynolds number (-)} 
\end{align*}

\( sg \)  
\begin{align*}  
\text{surface-gas direct exchange area (} & \text{m}^2\text{)} 
\end{align*}

\( xxiii \)
\( \bar{SG} \) surface-gas total exchange area \((m^2)\)

\( \bar{SG} \) surface-gas directed exchange area \((m^2)\)

\( ss \) surface-surface direct exchange area \((m^2)\)

\( \bar{SS} \) surface-surface total exchange area \((m^2)\)

\( \bar{SS} \) surface-surface directed exchange area \((m^2)\)

\( t \) time \((s)\)

\( T \) temperature \( (^{°C})\)

\( V \) volume \((m^3)\)

\( W_i \) leaving flux density \((W/m^2)\)

\( x \) coordinate

\( y \) coordinate

\( z \) coordinate

subscripts:

\( acc \) accumulation

\( amb \) ambient

\( back \) back face of the billet with respect to billet movement

\( bottom \) bottom face of the billet

\( c \) carbon

\( CO_2 \) carbon dioxide gas

\( comb \) combustion

\( eff \) effective

\( end \) end face of the billet

\( enth \) enthalpy

\( front \) front face of the billet with respect to billet movement

\( fuel \) fuel

\( g \) gas element

\( h \) hearth

\( H_2O \) water vapour

\( i \) element i

\( in \) pertaining to molar flows entering a gas volume

\( j \) element j

\( net \) net
$O_2$ oxygen gas

out pertaining to molar flows exiting a gas volume

r refractory (can be either applied to either the walls or the roof)

s surface element

st steel

top top face of the billet

wall wall

x $x$ coordinate

y $y$ coordinate

z $z$ coordinate

Greek alphabet:

$\alpha$ absorptivity (-)

$\delta$ Kronecker delta (-)

$\varepsilon$ emissivity (-)

$\pi$ pi (-)

$\rho$ surface reflectivity (-)

$\rho$ density (kg/m$^3$)

$\tau$ transmissivity (-)

$\theta$ angle between the normal of a surface element and the vector defined by $r$
Chapter 1: Introduction

Since the early 1980's, steel plants have been striving to develop mill-wide integrated control systems to reduce costs and increase productivity. This has lead to a critical reexamination of each stage of the steelmaking process, their relationship with downstream processes and, ultimately, the finished product. Unlike continuous casting and hot rolling operations, limited research has been carried out on the reheating process even though maintaining targeted discharge temperatures is imperative to ensuring uniform rolling conditions. The available literature has primarily focused on increasing steady-state productivity via significant design changes, such as the addition of bottom firing or the conversion from skids to walking beams, or relatively simpler measures, including new burner designs and better refractory selection. More recently, attention has focussed on improved furnace control during transient conditions, often relying on mathematical models to find optimal firing strategies. The driving force for these changes is the increasing competition among the steel producers to reduce the energy costs associated with bringing the steel to rolling temperatures while improving the quality of heating.\textsuperscript{1,2}

Fuel is a major cost associated with the operation of a reheating furnace.\textsuperscript{3} The particular companies of this study have recently entered into contracts where the natural gas costs have risen 25%.\textsuperscript{4,5} Steel companies are also faced with tighter pollution control standards and, in the case of the reheating furnace, this means improving control of the combustion process. For example, operators strive to minimize the amount of excess combustion air to improve thermal efficiency. However, if the furnace is fired too lean, even though above stoichiometric, there stands the risk of excessive carbon monoxide generation and also the formation of nitrogen oxides due to higher gas temperatures at the burners.\textsuperscript{6,7}

The reheating furnaces in most plants have been in operation for several years and furnace personnel have often developed unregulated practices that perhaps should be re-evaluated.\textsuperscript{1,2} These practices often result from the desire of mill operators to process steel at higher temperatures to minimize rolling forces. Besides requiring more fuel, excessively high temperatures can affect the metallurgical quality of the steel; for example scale formation,
Chapter 1: Introduction

decarburization or even surface melting. In mini-mills that use recycled steel, the residual copper may become concentrated near the surface as the iron becomes oxidized. Tensile thermal stresses produced during reheating may then cause cracks to initiate and propagate, a phenomenon called craze cracking. Given that different personnel may operate a particular furnace, the potential exists for the steel submitted to the rolling operations to have some variation in discharge temperature and surface quality. These issues lead to the concept of heating quality that is far more difficult to assess and control than simply drop-out temperature that is often the single parameter to which furnace control is directed.

Another incentive for improving the performance of the reheating furnaces is the emergence of competing technologies. In direct rolling technologies, slabs are cast in thinner dimensions and sent directly to the rolling operations, thus reducing the energy costs associated with reheating and roughing operations. However, because of this direct connection it is difficult to inspect the steel for surface flaws. Co-ordination between the casting machines and the rolling mills has to be maintained and upsets in the rolling stage can have severe repercussions on the casting operation. Given these issues, and the fact that they are already well entrenched at many existing steel plants, reheating furnaces will continue to operate provided they remain economically viable.

Whether the objective is to reduce fuel consumption, optimize current heating practices or remain competitive with newer processes, efforts directed at improving furnace operation can offer significant dividends. Traditionally, these efforts consisted of fine-tuning operating parameters through trial-and-error or the installation of more sophisticated furnace control equipment. Recently, however, furnace models are being used off-line to define optimal steady-state firing strategies. As computing power increases, these models are evolving into transient formulations to develop control strategies during furnace delays. Some of these models are further being utilized in an on-line capacity and thus have become integral components of the furnace control system.
Chapter 2: Literature Review

A comprehensive review of recent modernization programs at steel companies throughout North America has been compiled by Samways. Another review that primarily focuses on reheating furnaces has also been carried out by McManus. In most cases, furnace modifications have been directed at increasing productivity, improving fuel efficiency, and reducing pollutant emissions. The majority of the modifications involved the upgrading of furnace control systems, while others focused on refractory applications and burner design. Before discussing the impact of these changes on furnace operation, a general review of the design and operation of the reheating furnace will be useful.

2.1 The Steel Reheating Furnace

Reheating furnaces, such as the one shown in Figure 2.1, supply steel to the rolling mill at temperatures high enough to enable deformation processes to be carried out economically. They are fired on a variety of hydrocarbon fuels, including natural gas, blast furnace gas and coke oven gas. Burners may be installed in the roof or walls, both above (“top firing”) and below (“bottom firing”) the steel charge. To facilitate combustion, air is also injected through the burners. At some plants, the thermal load associated with bringing the air to combustion temperatures is reduced by either preheating the air using a recuperator or replacing some of the air with a stoichiometrically equivalent amount of oxygen, thus reducing the amount of nitrogen that has to be heated.

The charge, consisting of slabs or billets, is advanced through the furnace by either of two methods. The simplest method, which is found in “pusher-type” furnaces, is to butt each piece against the next to form a continuous “slab” that is advanced by forcibly adding more pieces. Because the elements of the charge are in contact, heating occurs on the top and bottom surfaces and, to a lesser extent, the end faces. The amount of force that can be applied to advance the charge is limited to prevent pieces from piling up inside the furnace, and thus limits the length of the furnace and the maximum throughput. In pushing the charge, significant frictional forces are transferred to the support structure that is encased in insulation and water-cooled in order to retain
its low-temperature strength. The heat removed by the coolant decreases the thermal efficiency of the furnace. Further, the frictional forces from pushing the charge introduce surface flaws on the bottom surfaces of the steel that are in contact with the support structure, or "skids".

The second method avoids these difficulties by incorporating a "walking-beam" design. Water-cooled beams located well below the steel are periodically raised to lift the entire charge and advance it to the next position. A gap is present between the charge elements resulting in each face being exposed to heat transfer. Without the frictional forces inherent in pusher-type furnaces, less support structure is required improving the thermal efficiency of the furnace since less coolant is used. However, these advantages are partially offset by higher capital costs and the increased maintenance associated with the water-cooled, walking-beams.

In both types of furnaces, the water-cooled support structure in contact with the charge introduces localized cold spots, or "skidmarks", in the steel. Depending on the design of the support structure and the operation of the furnace, the skidmark differential may be as high as 250°C. For pusher-type furnaces, this has led to the development of wear resistant, ceramic components, or "skid-buttons", to reduce the amount of heat conducted from the steel to the skids.
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(see Figure 2.2). These components must be strong enough to endure the frictional forces associated with advancing the charge. In comparison, the support structures in walking-beam furnaces, which are referred to as stationary beams, only need to bear the weight of the charge. They are primarily constructed from refractory materials, with a small amount of water-cooling employed to maintain low-temperature strength. For both types of furnaces, skidmark severity is further reduced by minimizing the amount of radiative shielding created by the support structure on the bottom face of the charge. It is estimated that 10-30% of the energy input into a slab furnace is removed by the skid system\(^{25}\), although some of this heat can be recovered as steam. The advantages of converting a pusher-type furnace to a walking-beam furnace are evident from a recent upgrade at Inland Steel, where fuel consumption was reduced by 18% and the skidmark severity was decreased by 40%\(^{27}\).

In most furnaces, the products of combustion flow counter-currently to the movement of the charge thus maximizing the mean temperature differential between the gas and the steel along the length of the furnace. The furnaces are divided into control zones that employ different firing rates depending on the local heating requirements for the steel. Larger furnaces are often physically divided into distinct chambers to improve temperature control. Although there are several variants, most furnaces have three axial zones: a charging (preheat) zone, a heating (tonnage) zone and a soak zone. In the charge zone, heavy firing is used to rapidly transfer as much thermal energy to the steel as possible. Due to the low thermal conductivity of the steel, this produces substantial temperature gradients with the interior temperatures being much colder than the surface. The heating zone is characterized by reduced, but still substantial, heating rates allowing thermal energy to be conducted from the surface of the steel to the interior. At this point, the steel has traveled about two-thirds through the furnace and substantial surface/interior temperature gradients and skidmarks still exist. The role of the soak zone, which uses lower firing rates that are adequate to maintain surface temperatures, is to provide time for the temperatures in the steel to homogenize. In fact, this cannot be achieved since residual skidmarks will remain under normal production rates.

To achieve the desired steady-state heating profiles, furnace operators follow specific
firing and pacing strategies for each steel grade and charge size. High production rates can lead to lower discharge temperatures or inadequate homogenization of surface/interior temperature gradients and skidmarks. With lower steel temperatures, higher rolling forces are required resulting in increased electrical costs and excessive roll wear. After rolling, regions of the steel that had skidmarks will possess different physical properties than the bulk material and this can be critical for certain finished products. These effects can be partially offset with higher firing rates, which lead to more fuel being consumed per tonne of steel or slower pacing rates. Higher temperatures reduce the required rolling forces; however, the steel surface quality may be affected by melting, oxidation or decarburization. Given these trade-offs, finding and maintaining the optimal firing strategy can be difficult, and this is especially true when furnace operation often deviates from steady-state.

The distribution of combustion energy in Dofasco's furnace is shown in the Sankey diagram in Figure 2.3. Based on the heat content of the supplied fuel, 63.0% of the combustion energy is absorbed by the steel and 39.3% is lost in the off-gas. Of the 39.3% lost to the off-gas, 15.0% represents energy recovered using a recuperator to preheat the combustion air. The wall and steam losses are lower at 5.1% and 11.2%, respectively.
2.2 The Objective, Methodology and Implementation of Automated Furnace Control

Levels of furnace control range from the manual control of zone firing to advisory systems that use mathematical models, expert systems or neural networks. Factors that influence the development of a control strategy are the company's production objectives, the availability of capital, and the amount of time required for implementation and operator training. The benefits can potentially include:

Reduction in fuel consumption. Because natural gas prices have been increasing since the early 1970's, reducing fuel consumption has traditionally been the primary objective. The control system adheres closely to the designated heating strategy and adjusts to process changes such as charge size, pacing rates and mill delays.

Increase in tonnage throughput. Delay management and the optimization of furnace
charging strategies, which groups together elements having similar heating profiles, increase the furnace throughput that may be partially offset by higher fuel consumption.

**Improvement of steel surface quality.** This is achieved by monitoring the furnace atmosphere and tracking the steel surface temperatures to prevent melting and minimize oxidation. The control system should also be able to predict the surface quality during furnace delays.

**Improved temperature homogenization in the discharged steel.** Providing adequate soaking times to homogenize interior temperatures allows for consistent deformation of the steel in subsequent rolling operations.

**Implementation of hot charging.** Hot charging preserves the sensible energy of continuously cast material by charging it into the furnace before it cools to ambient temperatures. The control system should be able to adjust for change-overs from cold to hot charging.

**Implementation of mill-wide integrated control.** Information from the rolling mills is fed back to the reheating furnace to ensure that the furnace and/or the mill is operating at full capacity and the product supplied to the rolling mills is adequately heated. Some plants operate under highly transient conditions, i.e. mill delays or cooling beds becoming full, requiring the heating strategy of the steel to be continuously modified.

A control system for slab reheating furnaces at Armco’s Middletown plant has been described by Cook *et al.* Shown schematically in Figure 2.4, it incorporates in-process measurements, slab heating models and information returned from the strip rolling operations. By monitoring the furnaces and the actions of different operators, the control system has led to more consistent heating. A simplified heating model is used to predict the effect of changing process variables from the current conditions, while a detailed model that incorporates radiative heat transfer operates in real time to ensure the projected temperatures are reasonable. To verify the models, a slab instrumented with thermocouples was connected to an insulated data logger and
charged into the furnace. Optical pyrometers were used to measure refractory temperatures by sighting through inspection doors in the furnace side walls. During normal operation, information from the strip rolling operation is used to correct for any drifting of the models that may occur.

The on-line system at Inland Steel incorporates a scheduling model to optimize slab charging. Lineups that randomly mix hot and cold slabs, slabs of different sizes and chemistry, and slabs requiring different discharge temperatures made furnace control difficult. After the lineup analysis model is executed, slabs having similar heating profiles were charged together (see Figure 2.5). Similar to Armco’s control system, rolling models in the mill were used to back-calculate slab discharge temperatures. A more recent review of this system described the implementation of a mathematical model. Model details were not given; however, both the furnace thermocouples and the predicted slab heating profiles are used to assess how the furnace should be fired. For example, when a furnace zone contains a transition between slabs having different heating requirements, a “positional weight factor” is calculated. This is preferable to an averaged temperature since it is biased towards the slabs leaving a zone, thus ensuring they are closer to the targeted temperature. The performance of the system has lead to better than 97% on-line supervisory control and the furnace energy consumption has been reduced from 1.49 million BTU/ton (rolled ton) in 1991 to 1.38 million BTU/ton by August of 1992 - a 7.3% reduction.

The control system developed by Roth et al contains models for fuel consumption, furnace heat transfer, scale formation and temperature losses in the roughing mill. These models were combined to produce a mill-wide control system shown schematically in Figure 2.6. The furnace model was verified using a slab instrumented with thermocouples that were connected to an insulated data logger assembly. In 1977, when this work was carried out, particular attention was directed at developing special strategies for periods when the mill was under a delay. The authors indicated that under operator control, adjustments to the zone temperatures were only made when the upsets were severe, further stressing the need for an on-line model that could automatically make these changes.
A new computer control system was recently included in an upgrade program for the reheating furnaces at Dofasco. The control system was designed to take into account a charge consisting of both cold and hot slabs as well as slabs of different chemistries and sizes. It relies on continuously updated heating profiles that are calculated from a database containing heating strategies generated by an off-line mathematical model. It was also noted that the development of a user-friendly interface was instrumental in encouraging plant personnel to adopt to the new control strategy.
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Figure 2.5: Example of an optimized lineup profile at Inland Steel.¹

Figure 2.6: Control system described by Roth.²³
More recently, Cameron described the development of these heating profiles and their continued refinement.\textsuperscript{30} For example in Figure 2.7, the lower curve with the solid line is the “desired temperature aim” whereas the upper solid curve is the “achievable temperature aim” calculated from the database. The difference is the projected slab overheating which, ideally, should be minimized. Control limits around the achievable temperature which are also shown in the figure were set to 20°C and it is apparent that the actual slab temperatures generally fall within these limits.

In implementing a control system at British Steel, Glatt and Macedo have developed “carpet” diagrams of the four main furnace variables: zone temperatures, slab temperatures, throughput and fuel flow (see Figure 2.8). Similar to the approach taken above, the control system relies on a database of past furnace performance to find the desired firing strategy. Furnace operators were involved in the development of the carpet diagrams as well as the overall design of the furnace control strategy. This led to additional features being implemented into the control system, including chart recorder output and visual display screens, that further increased operator interest and improved the consistency among different operators.

It is evident from these examples that reheating furnace control systems range from databases of previously determined heating strategies to systems employing mathematical models. With the common goal of delivering steel to the rolling mills at the targeted temperatures, they may additionally optimize the charging sequence, track the heating profiles of individual charge elements and invoke delay strategies that minimize fuel consumption. A critical stage in the development of these systems is the assessment of their performance. This often relies on feedback from the mill, including rolling forces and surface temperatures measured by an optical pyrometer. The measurement of steel temperatures while inside the furnace are necessary to establish the heating profiles of the charge and validate the heating models used for furnace control.
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Figure 2.7: Control of slab discharge temperatures at Dofasco.\textsuperscript{30}

Figure 2.8: A furnace control carpet diagram based on four key variables: heating zone temperatures, slab temperatures, throughput and fuel flow.\textsuperscript{18}
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2.3 The Measurement and Application of Temperatures in Furnace Control Systems

Furnace control usually involves zone temperatures measured by refractory encased thermocouples that are inserted through the roof or walls. Zone firing rates are then adjusted to minimize the difference between the set-point and measured temperatures. Because the thermocouples radiatively interact with other elements in the furnace, the measured temperatures are empirical in nature representing some form of average of the steel, refractory and combustion gas temperatures. Considerable effort is directed at determining the relationship between the zone set-point temperatures and the desired heating profiles for a given steel grade and charge size. These profiles are often measured by billets or slabs that are instrumented with thermocouples and charged into the furnace. More recently, optical pyrometers have been used to measure steel surface temperatures, from which a mathematical model can be used to calculate interior temperatures and the corresponding heating profiles.

Older and simpler control systems relied on empirical relationships to correlate zone temperatures to heating profiles. For example, Misaka et al. at Sumitomo Metal Industries' Kashima Steel Works, use the following relationship:

\[ q = 4.88 \Phi_{CG} \left[ \left( \frac{T_{zone} + 273}{100} \right)^4 - \left( \frac{T_{surface} + 273}{100} \right)^4 \right] \]  

(2.1)

The coefficient terms, \( \Phi_{CG} \), incorporate geometrical phenomena as well as the absorption and emission of thermal energy by the furnace gases. They were determined using a slab instrumented with thermocouples that was connected to an insulated data logger assembly (see Figure 2.9). This assembly also contained a water jacket such that thermal energy entering the data logger would be absorbed by the boiling water. The size of the datalogger assembly was 0.30 m high, 0.40 m wide and 0.68 m long, and measurements were recorded for up to five hours. Although furnace control using this type of relationship is both quick and simple, the coefficient values are only valid for the conditions under which they were obtained. For different charge sizes, steel grades, charging temperatures, or dropout temperatures, a new set of coefficients has to be deter-
Datalogger assemblies have also been used at other steel plants. At Armco, part of a slab was machined out to provide a “nest” for a Thermophil STOR recording device, which consisted of a battery powered digital recorder that was housed inside an insulated container (see Figure 2.10). Six thermocouples were used with the leads being placed in grooves that had been machined into the top surface of the slab. Initially, high furnace set-points and production delays caused the slab surface to melt destroying the thermocouples while the slab was in the heating zone. Subsequent modifications, including the repositioning of thermocouple leads down the sides of the slabs, enabled trials of up to four hours in length to be carried out.

Optical pyrometers capable of measuring steel surface temperatures inside of a furnace have recently been incorporated into control systems. In the products of combustion found in a reheating furnace, the principal absorbers of radiant energy in the near infrared spectrum are carbon dioxide and water vapor. Within this spectrum, windows of low gas opacity exist at 1.6, 2.2 and 3.9 μm as shown in Figure 2.11. An optical pyrometer that operates at one of these wavelengths measures an “apparent” steel temperature that consists of an emitted component from the steel surface as well as a component representing the multiple reflections of radiant energy from other surfaces within the enclosure. As indicated in Figure 2.12, the amount of reflected energy relative to emitted energy is reduced, but not eliminated, with increasing wavelength and an optical pyrometer operating at a wavelength of 3.9 μm is therefore used.

A typical industrial setup consists of one pyrometer measuring the apparent steel temperature and another measuring a background temperature (see Figure 2.13). At a wavelength of 3.9 μm, the background temperature should be “representative” of nearby refractory temperatures since the furnace gas does not interfere with the measurement. The numerical procedure for correcting the steel temperature with the background temperature is described by Hottel and an example of a typical correction, which is furnace dependent, is shown in
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Figure 2.9: Data logger/slab assembly employed by Misaka et al and measured slab heating profiles.

Figure 2.10: Thermophil STOR datalogger used by Cook and measured heating profiles for a 250 mm slab.
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Figure 2.11: Opacities of carbon dioxide and water vapor as a function of wavelength. (Gas temperature of 1350°C)\textsuperscript{14}

Figure 2.12: Ratio of reflected to emitted radiance as a function of wavelength for a billet at 800°C and varying mean background temperatures. (Surface emissivity assumed to be 0.8)\textsuperscript{14}
Figure 2.14. When the test slab was significantly colder than the roof refractory, the extent of the correction increased to about 100°C. For this reason, the optical pyrometers are generally located in the heat and soak zones. These systems are expensive (~$15,000 U.S.) because the pyrometers need to be water-jacketed and require air sparging to keep the optical lenses clean.

In addition to discharge temperatures, steel surface and interior temperatures while inside the furnace have been used to characterize the heating profiles. These are then incorporated into a control system via the zone set-point temperatures. However, there is little mention of including gas temperatures in these systems suggesting that rigorous calculations of fuel combustion and radiative heat transfer were not carried out. Because the flames and the products of combustion are the hottest components inside the furnace, firing rates will influence the amount of thermal energy that is transferred to the charge surface. Mathematical models of reheating furnaces are useful in providing a means for including these phenomena into a control strategy.

2.4 Mathematical Modelling of Reheating Furnaces

Besides calculating the heating profiles, mathematical models also generate new knowledge in terms of billet heating quality including surface/interior temperature gradients, skidmark severity, surface melting, and surface oxidation or decarburization. As indicated earlier, the majority of the furnace models have been used in an off-line capacity to generate databases of steady-state firing strategies. These have evolved into transient formulations that are also capable of developing firing strategies for mill delays. By using these models in an off-line capacity, only a limited number of scenarios can practically be examined. With increasing computing power, real-time and on-line "predictive" models are being developed that provide furnace operators with an overview of current conditions and the ability to predict the effects of changing certain process variables. The next stage is the direct incorporation of these models into the control systems to provide some degree of automatic control.

The development of mathematical models has, for the most part, been limited by the computational demands that are required to simulate radiative heat transfer within a reheating
Chapter 2: Literature Review

Figure 2.13: Schematic diagram of two 3.9 μm optical pyrometers used to measure steel surface temperatures inside of a furnace.

Figure 2.14: An example of the typical correction required for the measurement of steel surface temperatures inside of a furnace. 

34
furnace. Because the strength of energy emission varies with temperature to the fourth power, the solution of furnace temperatures is a strongly nonlinear problem. For example, the most popular modelling technique, Hottel's “Zone Method” (which is described in greater detail in Chapter 7), divides the furnace into a large number of isothermal surface and gas zones.\textsuperscript{40} This requires the solution of a large system of nonlinear, simultaneous equations involving “full” matrices. The formulation becomes even more complex when the effects of the furnace atmosphere are considered or when other phenomena are included, such as combustion, flames and furnace operation during mill delays. For these reasons, most models have had to employ simplifying assumptions.

In the early 1980's, Fontana \textit{et al} of Italipianti, a major reheating furnace supplier, developed a mathematical model to calculate steady-state slab temperature profiles.\textsuperscript{41} In this model, the furnace was divided into a number of transverse slices with radiative heat transfer within each slice being evaluated. Key modelling assumptions include the radiative exchange along the length of the furnace being accounted for in the gas temperature profile and the absence of heat and mass transfer between the regions above (upper chamber) and below the charge (lower chamber). Using an estimated gas temperature profile, the distribution of thermal energy to the steel and refractory in the first transverse slice was calculated. This process was then repeated for the remaining transverse slices using slab temperatures from the previous step. Following the calculation for the last transverse slice at the discharge end of the furnace, a global energy balance for the entire furnace was then performed. If convergence was not obtained, another iteration along the length of the furnace was implemented using an improved estimate for the gas temperature profile and usually five or six iterations were required for convergence. This type of model is referred to as a “marching” scheme and is limited to steady-state simulations. An example of Fontana's results depicting a typical steady-state slab heating profile is shown in Figure 2.15.

A similar, but much more detailed, pusher-type slab furnace model has been developed by Barr at the University of British Columbia.\textsuperscript{42, 43} Although the iterative scheme is similar to that
described above, this model also includes the furnace atmosphere in the radiative heat transfer calculations using the Zone Method and the radiative shielding effects on the bottom of the slabs that are caused by the skid support structure. The model was validated using data from Inland Steel's slab furnace with example slab heating profiles shown in Figure 2.16. In the charge zone where the steel is the coldest, the calculated heat flux to the top surface of the slabs was about 160 kW/m² decreasing to approximately 20 kW/m² in the soak zone. Barr suggested that the installation of a hearth in the soak zone would significantly reduce skidmark severity. A lateral shift, or offset, in the skids near the discharge end of the furnace would also serve to minimize the skidmarks.

A mathematical model of a walking-beam reheating furnace of Bethlehem Steel's plant at Lackawanna, New York, was developed by Stry and Felske. Being one of the few examples where billet heating was modelled, the heat transfer in the spacing between the billets, or gap,
required a two-dimensional solution domain along the centreline of the furnace. This formulation, which also used the Zone Method, did not account for heat transfer across the width of the furnace (i.e. along the length of the billets). It also relied on a specified gas temperature profile that was crudely estimated based on the firing rates. As shown in Figure 2.17, significant surface/interior temperature gradients were calculated for the end of the heating zone, but were eliminated by the time the billet was discharged from the furnace. The corresponding heat flux profiles shown in Figure 2.18 indicate a value of approximately 150 kW/m$^2$ in the charge zone. It was concluded from this study that scaling and decarburization could be reduced by increasing the billet pacing rate, and thus decreasing the residence time. However, skidmark severity would increase because the soaking time would also be reduced. The authors proposed that rapid billet heating could be achieved by increasing the size of the gap between billets or by increasing the furnace temperatures. These measures would likely translate into lower production rates and increased fuel consumption per tonne of steel, respectively.

Chapman et al.\textsuperscript{45,46} at Kansas State University have carried out parametric studies for radiative heat transfer in a steady-state, pusher-type furnace and a transient, batch furnace. Both
Chapter 2: Literature Review

Figure 2.17: Billet temperatures (°F) calculated by Stry.\textsuperscript{44} (a - end of the heating zone, b - furnace exit)

Figure 2.18: Calculated heat flux profile from Stry.\textsuperscript{44}
models used the Zone Method to calculate radiative heat transfer in three dimensions producing "global" models where the energy balances were satisfied directly. The models also incorporated a four-gray gas model to simulate the furnace atmosphere. In the steady-state furnace model, the gas was assumed to travel through the furnace under plug flow conditions with complete combustion occurring in each zone. Gas temperatures were calculated from an energy balance that accounted for the sensible energy of the products of combustion as they travelled through the furnace. Using surface heat fluxes calculated in the chamber module, temperatures in the refractory and the charge were then calculated. The new surface temperatures were then fed back into the chamber module and the process was repeated until the gas temperatures stabilized, and thus the slab temperatures were found. Because the transfer of thermal energy was primarily from the furnace gases to the charge, the authors showed that the calculated slab temperatures were not very sensitive to refractory emissivities for typical values greater than 0.5.

Li et al at the University of British Columbia also developed a steady-state, three-dimensional, pusher-type furnace model using the Zone Method. This model differed from the previous model in that it required the gas temperature profile to be specified. The effects of different furnace parameters, such as gas temperatures, slab push rates and steel grades, on the slab heating profiles and skidmark severity were examined.

Tucker and Ward developed a three-dimensional model of a pusher-type reheating furnace that was formulated to analyze transient conditions. The model used the Zone Method with the direct exchange areas having been evaluated with the Monte Carlo method. The authors indicated that the Monte Carlo method was useful for complicated furnace geometries; however, it was stated that the exchange areas were likely less accurate than what would be obtained using numerical integration with a fine grid size. It was further suggested that such errors were less important for "long furnace" models since the largest errors existed for "distant" zone pairs. The three-dimensional, transient formulation allowed for the simulation of mill delays or the start-up of the furnace where, for example, it was found that a 20% energy saving could be realized by modifying the current start-up firing strategy. In addition, the overheating of the first billets charged into the furnace, which was a known problem, would also be reduced.
2.4.1 SkidMarks

Several models have been developed to analyze skidmark formation.\textsuperscript{25,43,51} Because these models focussed on skid design, simplifying assumptions for the remainder of the furnace were required to maintain reasonable computing times. In a model developed by Howells \textit{et al} in 1972, the influence of different skid designs on skidmark severity in slabs was examined.\textsuperscript{51} Regions of the slab remote from the skids were assigned a fixed temperature of 1300°C with contact resistance, skid shape and skid insulation being the key variables that were examined. From this study, it was evident that skidmark severity entering the soak zone was important since it dictated the amount of soaking time that would be required. Ford \textit{et al} investigated the same variables; however, an attempt was made to also include furnace radiative heat transfer.\textsuperscript{25} It was found that skid mark formation was influenced not only by contact with the skids, but also by the radiative shielding on the bottom surface of the slabs caused by the skid support structure. The model developed by Barr, which was described earlier, was successful in examining the effects of skid design using an even more detailed furnace model.\textsuperscript{42,43} Calculated skidmarks for a slab eighty minutes into a pusher-type furnace is shown in Figure 2.19. Although the affected regions are relatively narrow in size, the colder steel will behave differently during rolling and thus produce a finished product with variable physical properties.

2.4.2 The Modelling of Furnace Transients

The control system at Inland Steel, which was described by Shenvar\textsuperscript{24}, uses an on-line mathematical model developed by Veslocki and Smith\textsuperscript{52}. Although a detailed formulation of the model was not given, it employed a two-dimensional formulation along the center-line of the furnace (see Figure 2.20), with heat losses to the skid structure and the walls being ignored. Slab and refractory temperatures were calculated using transient, one-dimensional, finite-difference formulations. The key inputs into the model included the slab pacing rate, zone firing rates, and slab charging temperature and the model was validated using an instrumented slab, although details were again not provided.
Chapter 2: Literature Review

For the development of delay strategies, the modelling approach was to establish a baseline condition represented by slabs of a certain thickness (230 mm) that were processed at a specific pacing rate (12.8 m/h). The model was executed with these conditions until it reached steady-state, after which time delays were then initiated and various responses implemented. With the simulated delay being fifteen minutes in each case, four strategies were reported in [52]: no change in firing during the delay, a 25% decrease in the primary (charge) zone firing rate during the delay, a 25% decrease in the primary and secondary (heat) zones, and finally, a 25% decrease in the firing rate in the primary and secondary zones, with the secondary zone remaining at this level for seventy-five minutes following the delay. The results from the first case are shown in Figure 2.21. During the delay the average slab temperatures at the end of the primary zone increased from 925°C to 1045°C, at the end of the secondary zone from 1190°C to 1235°C and at the end of the soak zone from 1225°C to 1235°C. The peak value for the average slab temperature at the end of the primary zone increased to 1055°C, fifteen minutes following the end of the delay. A similar peak at the end of the soak zone was observed 105 min. after the delay with the

Figure 2.19: Skid mark severity for slabs eighty minutes into a pusher-type reheating furnace (from Barr).42
temperature increasing to 1295°C. These results suggest that there is a sizeable lag time following a delay when peak dropout temperatures are observed.

The results from the fourth scenario are shown in Figure 2.22. It is evident from this figure that the revised firing strategy produced essentially the same results at the end of the primary zone, with a temperature increase of 100°C. However, at the end of the soak zone, the peak temperature following the delay was only 10°C higher than the steady-state value occurring 55 min after the end of the delay. Based on the improved control of the slab discharge temperatures demonstrated by the fourth firing strategy, a control strategy must account for the entire charge increasing in temperature during a delay and accordingly adjust the firing in each of the zones both before and after the delay.

Because the Inland Steel furnace consists of distinct zones, the authors used the mathematical model to develop a simplified slab temperature estimator. This estimator calculates the heat flux to the top surface of the slabs based on a regression of the zone firing rates, the slab surface temperatures and the fourth power difference between the zone temperature and the slab surface temperatures. Since this model was much faster than the original model, it was used on-line by the furnace operators to examine the effect of changing certain process variables.
Figure 2.21: Average slab temperatures exiting each control zone using the first firing strategy.\textsuperscript{52}

Figure 2.22: Average slab temperatures exiting each control zone using the fourth firing strategy.\textsuperscript{52}

A transient, mathematical model that has been used on-line in a furnace control system developed at BHP Steel has been described by Yuen.\textsuperscript{53} In addition to slab heating profiles, the model also calculates skidmark severity and scale thicknesses. Energy balances in each zone are calculated in real-time taking into account combustion energy, sensible energy in the products of combustion, and the thermal energy contained in the preheated air. The model is also capable of simulating automatic furnace control by adjusting the zone firing rates based on the differences between the zone temperatures and the set-point values. For example, changes in energy flux, which correspond to adjustments of the firing rates, for a change in the slab thickness from 230 mm to 290 mm are shown in Figure 2.23. From the two hour mark when the change-over in slab thickness was initiated, the firing in each zone increased in response to the thicker slabs.
entering that particular zone, beginning with the charge zone (Zone 1) and ending with the soak zone (Zone 4) two and a half hours later. Calculated steady-state scale thicknesses are shown in Figure 2.24, with a maximum of about 1.4 mm in the discharged slabs.

![Figure 2.23: Change in energy flux (firing rates) in response to a 60 mm increase in slab thickness.](image1)

![Figure 2.24: Scale thickness as a function of furnace position for a slab reheating furnace at BHP Steel.](image2)
Chapter 3: Objectives

It is apparent from the literature that mathematical models of reheating furnaces are becoming integral components of furnace control. However, despite their increasing popularity, few of the control models have been described in any detail in the open literature. Those that are revealed have employed simplifications, such as the specification of gas temperatures, in order to minimize the computational demands. Few have simulated the radiative characteristics of the furnace atmosphere or were formulated for three-dimensional heat transfer. Even fewer could model transient furnace conditions, let alone perform this task in real time, or faster. With increasing computational capabilities, the development of a rigorous model that incorporates these features, while remaining fast enough to be included in a furnace control system, becomes more feasible. The overall goal of the present work is to develop such a model.

The objectives of the present study are summarized as follows:

(i) To develop a transient, thermal model for the billet reheating furnaces of the participating companies.

(ii) To conduct plant trial campaigns on both furnaces to establish the thermal histories of the billets, gas and refractory during steady-state and transient conditions, and to use this data to validate the mathematical model.

(iii) To assess current furnace performance and examine the influence of key operating parameters such as firing and pacing rates.

(iv) To use the model to develop delay strategies for the participating companies.

(v) To examine other potential modes of furnace operation using the model, i.e. hot charging or preheated combustion air.
Although the model has been configured for the participating companies in this study, the modelling methodology can be applied to the simulation of other reheating furnaces. Many of the findings from the plant trials and the model are applicable to other operations as well. As a step towards producing a model that can be implemented into a furnace control system, it has been designed to operate on a PC platform. Although beyond the scope of the present work, the model will provide the means for expanding the knowledge base of an on-line Expert System for the reheating furnace that is being developed in parallel. This system is intended to provide furnace operators with improved delay response strategies and enable overall gains in heating quality.
Chapter 4: Techniques for the Acquisition of Plant Data

Several plant trial campaigns were conducted on billet reheating furnaces at two Canadian mini-mills with the objectives being:

(i) To obtain data for model verification.

(ii) To evaluate the performance of these furnaces as they are currently operated and identify areas where improvements are possible.

(iii) To develop techniques and instrumentation to establish a program where similar measurements could be used to evaluate other furnaces.

The campaigns carried out by UBC personnel, with the assistance of company personnel, are listed in Table 4.1. The data collected by UBC consist of billet temperatures, refractory temperatures (roof and wall), and furnace gas temperatures and oxygen contents. To develop an understanding of furnace conditions during the tests, these data were augmented with the company furnace logs. These contain zone thermocouple and set-point temperatures, natural gas and combustion air flows, and billet surface temperatures measured by an optical pyrometer located near the discharge end of the furnace. During the trials, these data were used by plant personnel to control current furnace operation; however, it will be shown in this study that a careful examination of these data allows for long term trends to be identified.

Rolling schedules are designed to maximize mill throughput by reducing the number of required roll changes. This leads to the companies processing a particular billet size for about two weeks. The projected date for a change-over in billet size is difficult to predict due to production considerations and the time required to change-over to a new billet size is about a day. For these reasons, the plant trial campaigns were focussed on a particular billet size and lasted for about a week. The consumption of materials such as thermocouple wire or gas suction tubes, which would fail because of the thermal shock associated with being pulled out of the furnace, also
Table 4.1: A listing of plant trial campaigns and billet tests that were conducted.

limited the length of the trials. Conditions on top of the furnaces were warm, at about 50°C, and the dusty environment required the regular cleaning of the equipment.

4.1 Billet Temperatures

Prior to UBC’s involvement in the project, Company A had developed a data acquisition system using a small, hand-held datalogger placed inside a steel box lined with insulation. Thermocouples that had been instrumented into a test billet would then be connected to the datalogger, the box packed and mounted to the end of the billet, and the entire assembly charged into the furnace. Microtherm™ insulation, which was very expensive (~$1000 per square meter),
had been purchased for this application since it had a very low thermal conductivity. In practice, however, the company found that the assembly did not work as satisfactorily as the original calculations had predicted. This was attributed to a breakdown of the insulation as it reached the higher temperatures. A similar test conducted by the company and attended by the author used an insulated box/thermocouple configuration depicted in Figure 4.1. The approximate dimensions of the box were 0.20 m (width) by 0.28 m (length) by 0.18 m (height). Each layer of insulation was 25 mm thick which resulted in final cavity dimensions of 0.10 m by 0.18 m by 0.08 m. Allowable temperatures of 65°C at the datalogger location were reached within 35 minutes and well below the target of 90 minutes.

As a result, billet temperatures were measured with 25-30 m lengths of Inconel sheathed, MgO insulated, type K thermocouples. This technique had been used successfully elsewhere but was more awkward since thermocouple wire had to be continuously fed into the furnace.\textsuperscript{53,54} The holes in the billets containing the thermocouples were drilled to specified depths using a 3.6 mm (9/64") diameter, diamond-tipped drill bit. The wire diameter was slightly smaller at 3.2 mm (1/8") which prevented the furnace atmosphere from penetrating into the hole and possibly contaminating the thermocouple bead. The thermocouples were secured into position, using Swage Locks\textsuperscript{TM}, while the billet was on the charge skid. As the billet traveled through the furnace, tension was maintained on the wires to ensure they didn't become hung-up on other billets. When the test billet was about to be discharged from the furnace, the thermocouples were disconnected from the data logger because the discharge of the billet resulted in a rapid pull on the wires. At this point, plant personnel used a cutting torch to free the wires so that they could be pulled back through the charge entrance.

Tests on the thermal drift for this type of wire at high temperatures were carried out by Furniss.\textsuperscript{55} This drift is attributed to the diffusion of aluminum and manganese from the sheathing material and the negative wire of the thermocouple (alumel) to the positive wire (chromel). For an exposure temperature of 1100°C for 200 hours, the drift is about -1°C. Given that the thermocouples have a 1% error to begin with (1% of 1100°C = 11°C), the drift is not significant since the combined service time of the wire used in this study was at most five hours as a result of
Chapter 4: Techniques for the Acquisition of Plant Data

Figure 4.1: A schematic diagram of the insulated box tested at Company A (the numbers refer to thermocouples).

The thermocouple wires worked well during the trials and were, on occasion, used more than once. Following each run, they were checked for changes in resistivity that would indicate possible contamination or shortages resulting from the wires being bent. With oxidation, the Inconel sheathing became brittle and care was required in coiling the wire after each test. It is believed that the failure of a few of the thermocouples while inside the furnace was a result of previous handling.

4.2 Gas Temperatures and Composition

Gas temperatures were measured using the gas suction pyrometer shown in Figure 4.2. The probe was inserted through previously existing holes in the roof and allowed to acclimate to furnace temperatures. The furnace gas was drawn through the alumina tube using a suction pump thus forcing the gas to pass over a Pt/Pt-10%Rh thermocouple bead. Initially, the outer tube was made of stainless steel; however, it became heavily oxidized while inside the furnace resulting in restricted gas flow. This problem was solved using a high purity alumina tube, but the probe then
required greater care in handling. The probes also suffered from thermal shock due to the repeated insertion and extraction of the probe from the furnace. It was found in the last trial that a thicker walled tube performed better.

With this design, the thermocouple bead is removed from the end of the probe and is therefore shielded from furnace radiation. The gas velocity being drawn through the tube has to be

Figure 4.2: A schematic diagram of the gas suction pyrometer used during the plant trials.
large enough for convection to be the dominant mode of heat transfer. From tests carried out on a muffle furnace at UBC, increasing levels of suction through the probe caused the thermocouple reading to asymptotically approach a maximum value. This represented the actual gas temperature and confirmed the suction pump could deliver the required suction. A gas velocity of about 8 m/s over the thermocouple bead, which corresponded to the maximum capacity of the pump, was used.

The 2.5 m of corrugated, tift tubing cooled the furnace gas allowing the moisture to be filtered out in order to protect the pump. The oxygen content, indicated as a percentage, was measured using a Bacharach OXOR® II hand held electronic gas analyzer with an accuracy of 0.8% of the reading. The carbon dioxide measurements, also indicated as a percentage, involved a chemical reaction cell with a slide rule guide, and because of the slide rule its reading error is estimated at about 2% CO₂.

As an approximation, combustion can be simplified by the following equation:⁵⁶

\[
C_m H_n + (1 + y) \left( m + \frac{n}{4} \right) \left( O_2 + 3.776N_2 \right) = m CO_2 + \frac{n}{2} H_2 O + y \left( m + \frac{n}{4} \right) O_2 + 3.776 \left( 1 + y \right) \left( m + \frac{n}{4} \right) N_2
\]  (4.1)

Since the pump on the suction pyrometer has a filter to remove the moisture in the products of combustion, the equation

\[
\text{oxygen reading} = \frac{y \left( m + \frac{n}{4} \right)}{m + y \left( m + \frac{n}{4} \right) + 3.776 \left( 1 + y \right) \left( m + \frac{n}{4} \right)} \times 100
\]  (4.2)

can be used to estimate the fractional excess air used for combustion, \( y \), in a given zone. For a natural gas mixture of 93% methane and the remainder ethane, \( m=1.07 \) and \( n=4.14 \). Using these val-
Chapter 4: Techniques for the Acquisition of Plant Data

ues, the excess air over a range of oxygen readings can be calculated and these are given in Table 4.2.

<table>
<thead>
<tr>
<th>Oxygen reading (%)</th>
<th>Excess air (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>9.5</td>
</tr>
<tr>
<td>3</td>
<td>15.0</td>
</tr>
<tr>
<td>4</td>
<td>21.2</td>
</tr>
</tbody>
</table>

Table 4.2: Conversion of oxygen readings (dry basis) to fractional excess air for a fuel that is 93% methane and the remainder ethane.

4.3 Refractory Temperatures

A Mikron monochromatic optical pyrometer at an operating wavelength of 3.9 μm was used to measure refractory temperatures. As indicated in the Literature Review, the opacities of both water vapor and carbon dioxide are zero at this wavelength (see Figure 2.11) and the pyrometer readings are not affected by the furnace atmosphere. The pyrometer unit is portable allowing for several temperature measurements to be made at various locations along the length of the furnace.

During the last two plant trial campaigns, a refractory plug having a diameter of 0.13 m (5") was fabricated from the same material as the roof refractory in Company A's furnace. It was instrumented with four thermocouples at the depths shown in Table 4.3 thus enabling the heat flux through the plug, and therefore the roof of the furnace, to be calculated. When it was inserted into the furnace, the working face of the plug was flush with the inside face of the roof. The plug also recorded the transient response of the furnace refractory due to changes in furnace operation such as during mill delays when the firing was turned down.

4.4 Logged Furnace Data

In addition to overall furnace performance during each trial, logged data are used to assess conditions prior to and during each billet test. Described in detail in the next two chapters, the
data primarily consist of zone thermocouple and set-point temperatures. At Company A, an optical pyrometer is also employed to scan surface temperatures after the billets have been discharged from the furnace and passed through a descaler. These temperatures are an important component of the company’s furnace control strategy, however, natural gas and combustion air flows were not being measured until the second plant trial. Conversely, natural gas flows are logged at Company B, but it was not until the second plant trial that an optical pyrometer was used to measure billet surface temperatures.

### Table 4.3: Thermocouple depths relative to the working face of the refractory plug.

<table>
<thead>
<tr>
<th>Thermocouple-type</th>
<th>Distance from the hot face (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1: S</td>
<td>4</td>
</tr>
<tr>
<td>#2: K</td>
<td>49</td>
</tr>
<tr>
<td>#3: K</td>
<td>99</td>
</tr>
<tr>
<td>#4: K</td>
<td>151</td>
</tr>
</tbody>
</table>

Chapter 4: Techniques for the Acquisition of Plant Data
Chapter 5: Characterization of the Billet Reheating Furnace at Company A

5.1 Furnace Overview

The billet reheating furnace at Company A is rectangular in shape measuring approximately 0.91 m high, 5.4 m wide and 17.4 m in length. The furnace is fired with natural gas and combustion air through roof burners that are arranged in eleven rows with four burners per row (see Figure 5.1). For control purposes, the burners are grouped into three zones that are not physically separated: a charge zone with sixteen burners, a heat zone with sixteen burners and a soak zone with twelve burners. The firing capacity of each burner, expressed in MBTU/h, is shown in the figure with the maximum capacity for each control zone given in Table 5.1. Lower capacity burners are installed near the side of the furnace to prevent overheating of the billet ends.

Control of each zone is facilitated by zone thermocouples (Pt-10%Rh) inserted through the west wall of the furnace. These thermocouples measure an averaged temperature of the combustion gases, refractory and nearby billets. Insertion through the side wall, as opposed to the roof, positions the thermocouples closer to the billets thus providing greater sensitivity to billet temperatures. At 17.4 m, the furnace is relatively short and, to maintain adequate production rates, the energy consumption is high at about 2.1 GJ/tonne of steel.

Inside the furnace, the billets are about 0.13 m above a refractory hearth and supported by water-cooled hearth blocks, or stationary beams. The 0.20 m (8") billets are charged on every second stroke, with each stroke also being 0.20 m. This results in a charge consisting of forty-two billets and, assuming a billet weight of about 1.5 tonnes, a total charge weight of about sixty-three tonnes. The 0.15 m (6") billets, or smaller, are charged on every stroke of 0.27 m (10.5") thus producing a gap of at least 0.11 m (4.5"). In this case, the charge consists of sixty-two billets and, at approximately 0.8 tonnes per billet, a total charge weight of about fifty tonnes. The pacing rate for the 0.15 m billets is quicker since the total charge weight is smaller and the surface area to volume ratio is larger, which allows for faster billet heating. Specific heating strategies for each product, which include zone set-points and pacing rates, were developed through experience and are available in the furnace pulpit.
Chapter 5: Characterization of the Billet Reheating Furnace at Company A

Figure 5.1: Plan view of Company A’s billet reheating furnace (the numbers beside each burner represents the rated maximum firing capacity in MBTU/h).
Chapter 5: Characterization of the Billet Reheating Furnace at Company A

<table>
<thead>
<tr>
<th>Zone</th>
<th>No. of burners</th>
<th>Total zone burner capacity (BTU/h)</th>
<th>Zone fuel flow rates (m³/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>64 (10⁶)</td>
<td>1746</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>64 (10⁶)</td>
<td>1746</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>24 (10⁶)</td>
<td>655</td>
</tr>
</tbody>
</table>

Table 5.1: Maximum rated firing capacities for Company A’s billet reheating furnace.

During the plant trial campaigns, a system developed by plant personnel in the 1980’s was used for the logging of furnace data. An IBM XT® computer running ASYST® recorded billet discharge times, zone measured and set-point temperatures, and “percent valve settings” (but not actual flows) for the natural gas lines in each zone. An optical pyrometer located near the discharge end of the furnace measured billet surface temperatures after descaling assuming an oxidized surface emissivity of 0.8. A schematic representation of a billet profile is shown in Figure 5.2. Approximately fifty readings are taken on one face of the billet from which billet average, maximum and minimum temperatures are calculated. The maximum temperature is usually measured from the billet ends, however, it is possible that the centre of the billet is the hottest. Two minimum temperatures representing the east and west side stationary beams are also recorded. If, after a four minute period, a billet is not discharged from the furnace, the system recorded the zone temperatures and percent valve settings.

In addition to improving furnace performance and developing delay strategies, the company had two particular areas of concern: (i) the cores of high carbon billets periodically melted, particularly as a result of a mill delay, and (ii) the ends of 0.20 m, high carbon billets would sometimes break open while in the charge zone. Since the top surfaces of the billets were heated at a greater rate than the bottom surface, it was thought that the resulting differential expansion would induce excessive thermal stresses within the billets. Smaller billets can respond to this stress by a slight “bowing”. However, in larger billets, the top face is under compression and the bottom face is in tension. Surface flaws on the bottom surface, or even interior flaws from casting, would then serve as crack initiation sites under tensile loading. Adding to this problem is the fact that, during casting, solute segregates to the centre of the billet which decreases the
5.2 Overview of the Plant Trial Campaigns

As indicated in Table 4.1, two plant trial campaigns were conducted at the company. The first trial during June 7-10, 1994, focussed on the heating of 0.20 m billets under both steady-state and transient conditions. Similar measurements were carried out during the second trial, Feb. 1-Feb. 4, 1995, while 0.15 m billets were being processed. During both trials, gas suction measurements (temperature and oxygen levels) were carried out through holes located in the roof of the furnace that originally contained the zone thermocouples before they were moved to the west wall. The locations of these holes are indicated in Table 5.2 and Figure 5.1. When the 0.20 m billets were being heated, the side burners in rows 1, 2, 3 and 8 were closed off. For the 0.15 m billets, the side burners in rows 1, 2, 5, 8 and 9 were closed.

During the first plant trial, the 0.20 m billets would sometimes tumble forward 90° while
Chapter 5: Characterization of the Billet Reheating Furnace at Company A

<table>
<thead>
<tr>
<th>Location</th>
<th>Description of port location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue</td>
<td>At elbow where the flue piping exits the building</td>
</tr>
<tr>
<td>Charge zone</td>
<td>Row 3, east-most burner: 0.28 m (15&quot;) south, 0.51 m (20&quot;) west</td>
</tr>
<tr>
<td>Heat zone</td>
<td>Row 7, west-most burner: 0.36 m (14&quot;) south, 0.46 m (18&quot;) west</td>
</tr>
<tr>
<td>Soak zone</td>
<td>Row 11, east-most burner: 0.36 m (14&quot;) south, 0.46 m (18&quot;) west</td>
</tr>
</tbody>
</table>

Table 5.2: Sampling locations used for the gas suction measurements.

being discharged from the furnace. The temperatures measured by the billet pyrometer would then represent the back (no rotation) or bottom face (90° rotation). Readings from the bottom face gave higher temperature differentials associated with the skidmarks and, therefore, billet rotation has to be considered when analyzing the pyrometer data. The rotation of the 0.15 m billets during the second plant trial was far less frequent.

The plant trial data were used to demonstrate the following:

(i) Mill throughput is primarily limited by the furnace for the 0.20 m billets and either the furnace or the cooling beds for the 0.15 m billets.

(ii) The furnace frequently operates under transient conditions.

(iii) The steady-state billet heating profiles indicate the soak zone is used for heating instead of temperature homogenization.

(iv) The billets continue to increase in temperature during mill delays even though the firing has been turned down.

A summary of the major findings from the logged furnace data and the experimental data for both plant trial campaigns is included at the end of this chapter.
Chapter 5: Characterization of the Billet Reheating Furnace at Company A

5.3 Results from the 0.20 m Billet Plant Trial Campaign - June 7-10, 1994

5.3.1 Logged Furnace Data

The logged furnace data, which are presented in chronological order in Appendix A, are not only important in characterizing conditions at the time that the UBC measurements were carried out, but also the long term performance of the furnace. The billet average, maximum and minimum temperatures versus the time of day for June 7, 1994, are shown in Figures A.1 and A.2. The data from the early morning represent the conclusion of rolling 0.15 m billets, with the 0.20 m billets having been rolled towards the end of the day. With each data point representing a billet, the discharge frequency was greater for the 0.15 m billets, which is also indicated by the steeper slope of the daily billet count profile during the early morning.

The sparse number of readings during the roll changeover from 10:00 to 17:00 represents the difficulties in configuring the rolling stands to the desired gauge for the larger billets. During this time, the furnace was full of steel and being idled in an attempt to prevent billet overheating. Once steady-state rolling was achieved, the average discharge temperatures vary, or "undulate", from about 1060°C to 1175°C and this could lead to a corresponding variation in the properties of the finished product.

The measured and set-point temperatures for the charge, heat and soak zones are shown in Figures A.3-A.5. During this plant trial campaign, the set-point temperatures were only recorded when the furnace was under automatic control. From about 2:30 to 6:00, the furnace was empty and being idled by firing in the soak zone. If the charge or heat zones were turned on, these zones would rapidly overheat owing to their larger burners and the controllers have therefore been configured to take this into account. Consequently, the measured temperatures in the charge and heat zones were below the "set-point" values.

The furnace was being charged from about 6:00 to 7:20, after which time the operator took control of the furnace because of the difficulties encountered in setting up the mill. This is indicated by the charge and heat zone set-point temperatures dropping to zero and thus the
controllers were turned off. During this period, the soak zone was also frequently turned off in an attempt to control the discharge temperatures of the billets. This firing strategy led to a gradual increase in the charge and heat zone temperatures suggesting that the billets in these zones were also increasing in temperature.

Once steady-state rolling was reestablished after the start-up, near 17:30, the charge and heat zones were returned to automatic control. Under steady-state operation, the desired billet pacing rate caused the temperatures in these zones to remain below the set-point values and thus the firing was at the maximum. The soak zone temperatures more closely followed the set-point temperatures indicating this zone was used to control the billet discharge temperature. After the delay the soak zone temperatures did not exhibit the same undulations that were observed in the billet average temperatures. This suggests that the soak zone temperatures were a poor indicator of the billet discharge temperatures that are affected by the small delays and heating conditions in the charge and heat zones.

Figure A.6 shows the maximum temperature differentials and standard deviations for the scanned billet faces plotted against the time of day. As the furnace approached steady-state operation, and the billet residence times decreased, the differential temperatures and standard deviations increased. Figures A.7 and A.8 show the same data plotted against the billet average and minimum temperatures (over the east stationary beams), respectively. In both cases, the temperature differentials and standard deviations increased with decreasing billet temperatures. Because this trend was more pronounced for the minimum temperatures, billet temperature homogenization was limited by the adequate soaking times required to reduce the skidmark severity. Lower minimum temperatures may cause a rolling stand to “trip out” thus producing a delay in the mill.

The first billet test was carried out on June 8, 1994, while the furnace was operating close to steady-state conditions. The logged furnace data for this day is given in Figures A.9 to A.16. The billet count profile shows a long period from 7:00 to 15:00 when the furnace was not in operation. This was due to a mill-wide shutdown for scheduled maintenance that occurs on every
second Wednesday. After this delay, the billet count profile showed a rapid return to steady-state rolling since the mill was already configured for the 0.20 m billets. Compared to the changeover in billet sizes on the previous day, this was an easier start-up for the furnace operator since the return to steady-state rolling could be more readily predicted.

The test billet was charged into the furnace at 23:24, when it was believed that the furnace had recovered from a short delay at 21:00 due to a changeover from high carbon to low carbon grades. Following this changeover, the average billet temperatures decreased because the discharge interval was reduced from 122 to 87 seconds. The difference between the maximum temperature and the average temperature increased from about 30°C for the high carbon billets to 100°C for the low carbon billets. The high carbon billets require a reduced heating rate to prevent the cores from melting or the billets cracking while inside the furnace.

The plots of measured and set-point temperatures for each of the zones are shown in Figures A.11 to A.13. As before, the measured temperatures in the charge zone were below the set-point values and this zone was fired at a maximum. However, in the heat zone, the temperatures were able to reach the set-points for the high carbon billets when the pacing was slower, from 17:30 to 19:30. This zone was only fired at a maximum for the low carbon billets that had the quicker pacing rate. For both billet grades, the soak zone temperature remained close to the set-points which is expected given that this zone is used to control the discharge temperatures of the billets.

The plot of the differential temperatures and standard deviations in billet temperatures versus time of day, Figure A.14, reveals an important problem with respect to furnace control. For the high carbon billets, there are two plateaus present that correspond to billet rotations of 0° and 90° when they were discharged from the furnace. The higher temperature differentials of the upper plateau are measured from the billets that have rotated 90° since this results in the bottom face being scanned. Although less clear, this effect can also be seen in the average temperatures shown in Figure A.9 suggesting that the furnace operator could have had difficulty interpreting the fluctuations in billet temperatures. When the differential temperatures and standard deviations
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are plotted against the billet average (Figure A.15) and minimum temperature over the east stationary beams (Figure A.16), the trend described earlier is again observed with decreasing average billet temperatures leading to higher temperature differentials.

The second billet test was conducted on June 9, 1994. The plots of billet temperatures versus time of day (Figures A.17 and A.18) indicate that there were some difficulties in delivering to the mill billets at a consistent temperature. The furnace was always operating under transient conditions due to the numerous small delays of less than thirty minutes. Although some of the stoppages corresponded to changes in the rolling schedule, the majority were observed to be related to the fine-tuning of the roll settings.

The measured and set-point temperatures for each of the zones, which are shown in Figures A.19-A.21, denote several instances where the charge and heat zones were switched from automatic to manual control. For most of the day, the measured temperatures in the charge and heat zones remained below the set-points indicating full firing. However, after 15:00, the heat zone and, sometimes, the charge zone were able to approach the set-point temperatures. This was due to the billets in these zones increasing in temperature during the delays, thus increasing the "averaged" temperature measured by the zone thermocouples when firing recommenced. Despite this transient operation of the furnace, the soak zone temperatures remained close to the set-points.

The differential temperatures and standard deviations in billet temperatures plotted against the time of day fluctuated because of the transient operation of the furnace. In some instances the differential temperature exceeded 150°C suggesting near steady-state operation when the skidmarks were not adequately soaked. Following each delay, the differential temperatures started at a low value, due to additional soaking times, and then increased to the steady-state values. When plotted against the billet average temperature (Figure A.23) and the minimum temperature over the east stationary beams (Figure A.24), the trend described earlier is again observed, but with considerably more scatter.
On the last day of the plant trial campaign, June 10, 1994, two important features were observed in the plots of billet temperatures versus time (Figures A.25 and A.26). Following a delay from 1:00 to 2:30, the billet average temperatures undulated about 100°C until 6:00. This suggests the operator had some difficulty controlling the furnace even though the billet throughput following the delay was steady. Difficulties were also encountered in the mill at about 13:00 when the roll settings were changed for a high carbon product. This is indicated by the gradual increase in the daily billet count from 13:00 to 19:00 and the sporadic release of billets during this period. When this heat was completed, the mill was again reconfigured from 19:00 to 20:00 for low carbon billets, after which time the discharge temperatures again stabilized. Based on the logged furnace during this campaign, it can be concluded that the high carbon billets were more difficult to process which led to transient furnace operation.

The measured and set-point temperatures for each of the zones are shown in Figures A.27 to A.29. During the changeover to the high carbon billets, the charge and heat zones were turned down, however, the soak zone was still firing to ensure the billets were available for rolling while the mill was being configured. The plots of differential temperatures and standard deviations in billet temperature versus time of day are shown in Figure A.30. The differential temperatures of the billets discharged during the changeover are reduced since these billets have resided in the furnace for an extended length of time.

Calibration curves to convert percent valve settings to actual natural gas flows were not available at the company. It was therefore decided that these curves would be generated by plant personnel at the conclusion of the plant trial. However, due to an upgrade in the furnace controls, the percent valve settings were no longer being measured and the calibration could not be carried out. In any event, these data would have had limited value since the combustion air flows were not measured at the time of the trials.

5.3.2 UBC Measurements

In the first billet test (A1-1), a low carbon billet 4.78 m in length was charged into the
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furnace at 23:24 on June 8, 1994. It was instrumented with Inconel sheathed thermocouples at the locations given in Table 5.3. This test was designed to investigate billet heating along the centreline of the furnace while it was operating near steady-state. Since there was some experience with billets cracking inside the furnace, the thermocouples were positioned at least 50 mm from a given face. The discharge interval for the billets during the test was 87 s. The measured billet temperature profiles are shown in Figure 5.3 from which three important observations can be made. During the test, the measured billet temperatures varied by less than 100°C suggesting good temperature homogeneity. This may be due to the thermocouples being well removed from a given surface where the temperatures would be higher.

With a billet residence time of 58 min., the discharge temperature was approximately 1210°C and about 50°C hotter than the maximum surface temperatures of the previous billets that were scanned by the optical pyrometer (Figure A.9). These temperatures are near the upper working limits of type K thermocouples; however, the higher readings suggest the billet surfaces were quenched by the descaler that is located ahead of the pyrometer. For the company, this explained why the billet cores of the high carbon billets sometimes melted even though the pyrometer temperatures indicated otherwise.

The measured temperature profiles reveal that the “soak” zone was used for substantial heating and illustrates one of the difficulties encountered when pushing the production rate beyond the designed capacity. The company has a good qualitative understanding of the furnace’s capabilities and how heavily it can be pushed in order to achieve the required discharge temperatures at acceptable skidmark levels. However, the lack of a soaking stage makes the discharge temperatures more prone to process fluctuations, for example short delays in the mill.

The gas suction pyrometer measurements are given in Table 5.4. The flue gas temperature was 1138°C and represents a significant amount of lost thermal energy since a recuperator is not used. As mentioned earlier, the charge zone was fired at a maximum, however, the gas temperature in this zone was the lowest of all three zones at 1304°C. This is due to the furnace
gases radiating thermal energy to the colder steel that is present in this zone. The flue gases are colder than the furnace gases in the charge zone for two reasons: (i) the gases continue to radiate thermal energy to the billets underneath the flue and (ii) there is likely some infiltration of leakage air through the charge entrance. However, the oxygen reading in the charge zone at 2.8% was similar to the flue reading of 2.6%.

The gas temperature in the heat zone was the hottest at 1436°C and was approximately 200°C greater than the measured zone temperatures at this time. The low oxygen reading at 0.6%
indicates richer firing compared to the charge zone. The soak zone was also fired very rich with 0.5% oxygen in the products of combustion, but the gas temperature was 46°C colder than the heat zone. This may be due to the smaller burners giving lower firing rates or the additional thermal energy that is removed by the water-cooled discharge door. For the combustion of natural gas at 0% excess air the carbon dioxide concentration should be about 12% on a dry basis. The carbon dioxide measurements indicate that complete combustion occurred in all of the zones within measurement error.

A high carbon “prime” billet (4.52 m in length) was used for the second billet test (A1-2). It was charged into the furnace as part of a heat of high carbon billets at 20:46 on June 9, 1994. The use of prime billets represented a production loss and it was initially agreed that this billet would be used for two tests. However, because of past problems in heating the high carbon billets, it was later decided that the billet would only be passed through the furnace once. The locations of the five thermocouples used in this test are listed in Table 5.5.

Because of an electrical problem at approximately 21:30, billet heating during an unscheduled mill delay was measured during the test. The delay strategy was to turn down the firing in the charge and heat zones and reduce the firing in the soak zone to levels that maintained billet temperatures for rolling while keeping the burners lit. The billet heating profiles shown in Figure 5.4 level off 55 min. from the start of recording while the test billet was in the heat zone. At the start of the delay, the measured temperature differential was approximately 100°C and

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<table>
<thead>
<tr>
<th>Zone</th>
<th>Gas temperature (°C)</th>
<th>%O₂</th>
<th>%CO₂</th>
<th>Pyrometer reading (°C) (E)</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
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<td>Flue</td>
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<td>Soak</td>
<td>1390</td>
<td>0.5</td>
<td>16</td>
<td>1363</td>
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Table 5.4: Gas suction and optical pyrometer measurements for June 8, 1994.
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<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Location Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Centreline of the billet, 92 mm depth</td>
</tr>
<tr>
<td>2</td>
<td>Centreline of the billet, 305 mm from the east end, 97 mm depth</td>
</tr>
<tr>
<td>3</td>
<td>Middle of the furnace, 143 mm depth</td>
</tr>
<tr>
<td>4</td>
<td>Middle of the furnace, 51 mm depth</td>
</tr>
<tr>
<td>5</td>
<td>51 mm from the front face, 92 mm depth</td>
</tr>
</tbody>
</table>

Table 5.5: Thermocouple layout for billet test A1-2.

The measured discharge temperatures were much higher because of the delay, ranging from 1280°C to 1315°C. These readings are well into the upper limits of the reliable working range of the thermocouples, however, it is likely that the cores of these high carbon billets had melted. The temperatures from the second thermocouple, which is located in the middle of the billet but 0.30 m from the east end where cracking was known to occur\(^1\), are similar to those of the other thermocouples. This suggests that failure is due to surface/interior or top/bottom temperature gradients as opposed to differences along the length of the billet.

The gas suction measurements given in Table 5.6 were taken when the charge was moving and all of zones were being fired. The gas temperatures were higher than the previous day with a measured value of 1489°C in the heat zone following the stoppage. Because the billets homogenized in temperature during the delay, the driving force for the billets to absorb more thermal energy after the delay was reduced. This results in the furnace gases retaining the combustion energy and thus produced the higher temperatures.

The third billet test (A1-3) was conducted on June 10, 1994, and also measured billet heating while the furnace was operating closer to steady-state. The low carbon billet that was used in the first test was recycled for this test with the locations of the thermocouples given in

\(^1\) This phenomena was nicknamed a “clinker failure” because of the sound it is reported to make.

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Table 5.7. The discharge interval for the billets during this trial was 141 s and the highest among the three billet tests.

The measured billet temperatures again suggest that the heating was fairly homogeneous (Figure 5.5). In addition, the temperatures leveled off in the soak zone because of the longer billet discharge interval thus providing some degree of soaking. Despite the longer residence time of 88 min., the discharge temperature was similar to the other tests at about 1230°C. The influence of the stationary beams was relatively small with temperatures being approximately 125°C below the centreline temperatures in the charge zone, noting that the thermocouple was about 50 mm above the hearth block.

The gas temperature in the charge zone was slightly higher at 1411°C, but lower in the heat and soak zones at 1266°C and 1246°C, respectively (Table 5.8). Because the heat and soak zone temperatures reached the set-point values, these zones were not heavily fired. The charge
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<table>
<thead>
<tr>
<th>Zone</th>
<th>Gas temperature (°C)</th>
<th>%O₂</th>
<th>%CO₂</th>
<th>Pyrometer reading (°C) (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Wall (0.9)</td>
</tr>
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<td>Flue</td>
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<td>2.2</td>
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<tr>
<td>Charge</td>
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<td>Soak</td>
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Table 5.6: Gas suction and optical pyrometer measurements for June 9, 1994.

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Centreline of the billet, 98 mm depth</td>
</tr>
<tr>
<td>2</td>
<td>Centreline of the billet, 148 mm depth</td>
</tr>
<tr>
<td>3</td>
<td>Centreline of the billet, 51 mm depth</td>
</tr>
<tr>
<td>4</td>
<td>Over the east-most hearth block, 137 mm deep</td>
</tr>
</tbody>
</table>

Table 5.7: Thermocouple layout for billet test A1-3.

![Figure 5.5](#1: centreline, #2: bottom, #3: top, #4: bottom over skid)

Figure 5.5: Measured temperature profiles for billet test A1-3 on June 10, 1994.
Chapter 5: Characterization of the Billet Reheating Furnace at Company A

<table>
<thead>
<tr>
<th>Zone</th>
<th>Gas temperature (°C)</th>
<th>%O₂</th>
<th>%CO₂</th>
<th>Pyrometer reading (°C) (E)</th>
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<tr>
<td></td>
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<td>Wall (0.9)</td>
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<td>Heat</td>
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<td>9, 9</td>
<td>1242</td>
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<tr>
<td>Soak</td>
<td>1246</td>
<td>1.0</td>
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</tr>
</tbody>
</table>

Table 5.8: Gas suction and optical pyrometer measurements for June 10, 1994.

Zone was fired at a maximum and, with the slower pacing rate, the heat and soak zones have to do less work in bringing the billets to rolling temperatures. The oxygen content was consistent at 1.0-1.1 percent in all of the zones indicating good combustion conditions.

5.4 Results from the 0.15 m Billet Plant Trial Campaign - Feb. 2 - 4, 1995

The primary objective of the second plant trial campaign was the measurement of gas flow rates, particularly during a furnace delay. In the month before this campaign, Rosemount pressure transducers were installed in each zone to measure both natural gas and combustion air flows. However, the Rosemount readings were not being logged and had to be manually recorded during the trial. Expressed as percentages of 152 mm (6") of water column, the readings fluctuated approximately +/- 10% and, therefore, median values were recorded. The procedure for converting the pressures to gas flow rates is described in detail in Appendix B.

As part of furnace upgrade program, a new electronic controller was installed in the charge zone. Because of these changes, the ASYST/XT data logging system was no longer recording percent valve settings or zone set-point temperatures. This meant that the gas flow data could not be calibrated to the percent valve settings that were recorded during the first trial. The loss of the set-point data also meant that the firing strategies of the furnace operators, such as during delays when the firing was turned down, could no longer be interpreted. New controllers were installed in the remaining zones following the second plant trial campaign.
Another significant change was the installation of new mesh curtains at the charge entrance to limit thermal energy losses. The curtains helped to maintain a positive furnace pressure preventing cold, leakage air from being drawn into the charge zone. From this change alone, it was apparent that the furnace was operating more efficiently than during the first campaign.

This campaign focussed on the heating of 0.15 m billets since these also make up a major proportion of the company’s production. Four test billets that were slightly high in carbon (0.2-0.3%C) had been selected and predrilled by the company. A “prime” high carbon billet (1090 ball stock) was also provided from the production stream. In general, the lower residence times for the 0.15 m billets meant that the gas measurements had to be taken more quickly. Although every attempt was made to obtain a complete set of data, this was not always possible.

5.4.1 Logged Furnace Data

Two billet tests, A2-1 and A2-2, were carried out on Feb. 2, 1995. Compared to the 0.20 m billets, the pyrometer measurements, which are shown in Figures C.1 and C.2, indicate that the billet discharge temperatures were generally steadier. The daily billet count exceeded 1300 billets and was twice the daily production of the 0.20 m billets. The longer furnace stoppages that were observed in the first trial are absent in the billet count profile, suggesting that the 0.15 m billets were easier to process. Until 4:15, the discharge interval for the high carbon billets was 63 s and, after a one hour delay to convert the mill, the discharge interval decreased to 51 s for a low carbon product. These discharge intervals are about half a minute faster compared to the 0.20 m billets.

Because the billet temperatures were relatively steady, few changes were made to the furnace set-points as shown in Figures C.3-C.5. These figures demonstrate that the set-point temperatures were no longer zeroed when the furnace was placed under manual control. Changes to the overall firing of the furnace can be inferred from a rapid decrease in zone temperatures, for example at 14:30. However, a decrease in the firing rate in either the charge, heat or soak zones will cause the charge zone temperatures to drop because this zone is downstream. The charge
zone temperatures were generally much closer to the set-point values compared to the first plant trial. This may be a result of the new electronic controls in this zone or the smaller billets having a higher surface area/volume ratio, and therefore more rapidly heated under the same conditions. The heat and soak zones temperatures were also close to the set-points suggesting an overall improvement in furnace control and thus more consistent billet heating.

The plot of differential temperatures versus time of day (Figure C.6) further demonstrates the consistent heating of the 0.15 m billets, particularly towards the end of the day. Because these billets did not tumble when they were discharged from the furnace, steady-state temperature differentials of 100-125°C were measured by the pyrometer on the back faces of the billets. When plotted as a function of billet average (Figure C.7) and minimum temperatures over the east hearth block (Figure C.8), decreasing discharge temperatures resulted in larger temperature differentials.

The third billet test (A3-3) was carried out on Feb. 3, 1995. The billet discharge temperatures shown in Figures C.9 and C.10 remained steady until the scheduled delay at 10:30. This delay was required to change the gauges in rolls for a different product and, based on the gradual increase of the billet count profile, difficulties were encountered in re-establishing steady rolling. This in turn led to wide variations in the discharged billet temperatures following the delay. Approximately 1150 billets were discharged from the furnace because of the two delays occurring on this day.

The charge zone temperatures were close to the set-point values until the delay at 10:30 (Figure C.11). The firing was turned down during the delay producing the rapid decrease in the measured zone temperatures. When the furnace was emptied at 18:30, the charge zone temperature exceeded 1225°C which is well above the set-point of 1130°C. It is likely that the firing in this zone was not properly turned down even though billets were no longer present in the zone. Similar plots for the heat (Figure C.12) and soak zones (Figure C.13) demonstrate that the temperatures in these zones also exceeded their set-points at the same time. Heavily firing the
furnace while it is nearly empty can cause it to overheat and possibly damage the refractory.

The differential temperatures shown in Figure C.14 also indicate steady furnace operation before the delay. Afterwards, they were much lower due to the longer soaking times of the billets that were in the furnace during the delay. When plotted against the billet average temperature (Figure C.15) and the minimum temperature over the east-most stationary beam (Figure C.16), the trend described earlier is again present.

On Feb. 4, 1995, when the fourth billet test (A2-4) was carried out, the rolling mill had processed all of the billets that were available in the billet yard. This billet shortage was due to problems in the caster and demonstrates the dependency of the mill on upstream processes. Two long delays, from 8:15 to 10:45 and 15:00 to 20:00, are shown in the billet count profile in Figures C.17 and C.18. These delays were a result of the mill having to wait for billets to be cast and cooled in the billet yard. After the first delay, warm, low carbon billets were charged into the furnace and following the second delay, warm, high carbon billets were then charged. In these situations, the furnace set-points are no longer applicable and the operator has to rely on his experience to control the discharge temperatures. Approximately 975 billets were discharged from the furnace on this day which represented the lowest production observed during the campaign.

Difficulties were encountered in setting up the mill to roll the high carbon billets and this is shown by the gradual increase in the billet count profile following the second delay. The slowed production rate allowed the next heat of low carbon billets to cool while in the billet yard, and the test billet was charged into the furnace at 21:55 near the middle of this heat. The billet was supposed to remain in the charge zone for a scheduled delay of 10 min. in order to resize the mill for the low carbon billets. However, a blown entry box in the sixth roughing mill caused a longer delay from 22:00 to 23:00.

Before the first delay, the measured temperatures were close to the set-points in each zone
as shown in Figures C.19-C.21. After the first delay, the furnace operator was continually changing the firing rates in each zone in response to shorter delays that were caused by further adjustments to the roll settings. By following this strategy, the operator was successful in maintaining the billet average discharge temperatures at about 1125°C. In Figure C.22, the differential temperatures of the billets immediately following the delays decrease in response to the longer residence times. This is particularly true for the second delay when the billets in the soak zone were deliberately being held at rolling temperatures while the mill was being configured.

### 5.4.2 UBC Measurements

The first billet test (A2-1) on Feb. 2, 1995, used a low carbon billet having a length of 4.78 m. The thermocouple layout given in Table 5.9 was designed to measure the steady-state billet heating profiles along the furnace centreline. The billet was charged into the furnace at 12:39, with a discharge interval of 51 s, and a log of furnace conditions recorded during the test is given in Table 5.10. With reference to the corresponding plot of billet temperatures and billet count versus time of day (Figure C.1), this test was therefore carried out while the furnace was operating close to steady-state.

The thermocouple profiles shown in Figure 5.6 indicate the soak zone was used for substantial heating of the six inch billets in order to meet the required throughput. As expected, the thermocouple below the top face of the billet (76 mm deep from the front face and 19 mm below the top surface) recorded the fastest heating rate and was as much as 200°C hotter than the centreline temperature. The thermocouples near the front face and front/bottom corner increased in temperature more rapidly that the centreline or bottom thermocouples. This suggests that billet heating was influenced by heat transfer in the gaps between the billets. The dip in the temperature profiles 60 min. into the test was due to a short delay of unknown causes when the firing was temporarily turned down. At approximately 1255°C, the discharge temperature was about 90°C higher than the billet average temperatures measured on adjacent billets by the pyrometer. This difference was larger than what was observed with the 0.20 m billets during the previous
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<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>all thermocouples near the furnace centreline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>centreline of the billet, 73 mm deep</td>
</tr>
<tr>
<td>2</td>
<td>centreline of the billet, 112 mm deep</td>
</tr>
<tr>
<td>3</td>
<td>19 mm below the top face, 74 mm deep from the front face</td>
</tr>
<tr>
<td>4</td>
<td>19 mm from the front, 73 mm deep</td>
</tr>
<tr>
<td>5</td>
<td>19 mm from the front face, 123 mm deep</td>
</tr>
</tbody>
</table>

Table 5.9: Thermocouple layout for billet test A2-1.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:30</td>
<td>51 discharge interval and 26.7 cm stroke distance - furnace running steady</td>
</tr>
<tr>
<td>12:39</td>
<td>billet charged into the furnace</td>
</tr>
<tr>
<td>12:45</td>
<td>refractory plug in the charge zone: #1 1121°C, #2 957°C</td>
</tr>
<tr>
<td>13:00</td>
<td>gas suction in the charge zone: 1459°C, 0.9% O₂, 10.0% CO₂</td>
</tr>
<tr>
<td>13:20</td>
<td>Flow rates Charge zone Heat zone Soak zone</td>
</tr>
<tr>
<td></td>
<td>Gas 1.67 0.83 0.33</td>
</tr>
<tr>
<td></td>
<td>Air 15.94 8.98 3.77</td>
</tr>
<tr>
<td></td>
<td>Excess air, % -3.2 9.7 14.2</td>
</tr>
<tr>
<td>13:33</td>
<td>short furnace delay with test billet ~4 m from discharge door</td>
</tr>
<tr>
<td></td>
<td>gas suction in heat zone: 1518°C - probe broke</td>
</tr>
<tr>
<td>13:45</td>
<td>pyrometer reading in heat zone, ε=0.9: wall 1138°C, roof 1134°C</td>
</tr>
<tr>
<td>13:50</td>
<td>billet discharged from the furnace</td>
</tr>
<tr>
<td>14:00</td>
<td>refractory plug in charge zone: #1 1104°C, #2 950°C</td>
</tr>
</tbody>
</table>

Table 5.10: Log file for billet test A2-1. (flow rate: x10³ m³/h)

Natural gas flow rates in the charge, heat and soak zones at 13:20 were estimated to be 1,671 m³/h, 830 m³/h and 334 m³/h, respectively. The corresponding air flow rates were 15,942 m³/h, 8,976 m³/h and 3,766 m³/h. The fact that the charge zone was fired much more heavily than either the heat or soak zones agrees with the earlier observation that the measured temperatures in the charge zone remained below the set-point values while the other zone temperatures were closer to the set-points. These gas flows resulted in deficient combustion air in the charge zone at -3.2%, and excess air at 9.7% and 14.2% in the heat and soak zones. The
negative value in the charge zone suggests the fuel was not fully combusted, however, oxygen contained in the products of combustion from the zones upstream would also be used for burning the fuel.

It would be beneficial to reduce the amount of excess air in the soak and heat zones since high oxygen levels in these zones encourages scale formation. The nitrogen burden associated with the excess air further reduces the thermal efficiency in these zones. A more desirable configuration would see the soak and heat zones fired at combustion air levels just above stoichiometric and employ about ten percent excess air in the charge zone to ensure complete combustion of the furnace gases before exiting via the flue.

The charge zone gas temperature of 1459°C was, as expected, several hundred degrees higher than the recorded zone temperature of approximately 1100°C. The heat zone gas temperature was 1518°C and the probe failed before oxygen and carbon dioxide measurements

![Figure 5.6: Measured temperature profiles for billet test A2-1 on Feb. 2, 1995.](image)
could be made. These gas temperatures were approximately 50°C higher than those recorded during the first plant trial campaign. The company practice is to process the low carbon, 0.15 m billets at the fastest rate that the mill can support. This results in the furnace being fired more heavily and, when they occur, delays are likely a result of the cooling bed becoming full. Optical pyrometer readings for the heat zone were 1134°C and 1138°C for the roof and wall, respectively. As expected, the refractory was hotter than the zone thermocouples but colder than the furnace gases.

The second billet test (A2-2) was conducted on the same day and provided another opportunity to examine steady-state furnace operation. For this test, a high carbon billet (0.83%C) 4.9 m in length was used to determine whether the heating profile was different compared to the low carbon billets. The test billet was charged at 16:39 when the furnace had recovered from a short delay to reconfigure the mill. In spite of the high carbon, the fact that these were 0.15 m billets that were not being used for ball stock permitted a faster discharge interval of 47 s. The thermocouple layout for this test is given in Table 5.11 and the log file is presented in Table 5.12.

The heating profile was similar for about 45 min. after which time the temperatures of the centreline and top thermocouples began to drift. Since both thermocouples started to drift at the same time, it is unlikely that they had failed. During the next day, the same operator was observed to have opened a side door in the soak zone in order to introduce cold air and bring down the zone temperatures. This is an unregulated practice and whether it occurred during this test cannot be confirmed. Without this deviation, the billet discharge temperature would have been close to 1230°C. The excess air in the soak zone was 12.8% and this is in good agreement with a gas suction oxygen measurement of 2.1%. The gas suction temperatures of 1452°C in the charge zone and 1502°C in the heat zone are relatively high agreeing with the measurements from the first test.

The third billet test (A2-3) on Feb. 3, 1995, involved a low carbon billet having a length of 4.78 m. It was instrumented in a similar manner (Table 5.13) to the previous two tests, however, the objective of this test was to record the transient heating of a billet during a planned delay. The delay, from 10:30 to just after 12:00, was due to a sizing change in the mill and at 110 min. was
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<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Centreline of the billet, 75 mm deep</td>
</tr>
<tr>
<td>2</td>
<td>Centreline of the billet, 127 mm deep</td>
</tr>
<tr>
<td>3</td>
<td>19 mm below the top face 73 mm deep from the forward face</td>
</tr>
<tr>
<td>4</td>
<td>19 mm from the back face, 77 mm deep</td>
</tr>
</tbody>
</table>

Table 5.11: Thermocouple layout for billet test A2-2.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:44</td>
<td>Refractory plug in charge zone: #1 1104°C, #2 947°C</td>
</tr>
<tr>
<td>16:47</td>
<td>Test billet charged - furnace firing steady</td>
</tr>
<tr>
<td>17:00</td>
<td>Gas suction charge zone: 1452°C, 1.2% O₂, 9.0% CO₂</td>
</tr>
<tr>
<td>17:07</td>
<td>Pyrometer in charge zone, ε=0.9: roof 1159°C, wall 1234°C</td>
</tr>
<tr>
<td></td>
<td>Charge zone</td>
</tr>
<tr>
<td>Gas</td>
<td>1.39</td>
</tr>
<tr>
<td>Air</td>
<td>13.99</td>
</tr>
<tr>
<td>Excess air</td>
<td>2.2</td>
</tr>
<tr>
<td>17:20</td>
<td>Gas suction in the heat zone: 1502°C, 1.0% O₂, 11% CO₂</td>
</tr>
<tr>
<td>17:40</td>
<td>Refractory plug in the charge zone: #1 1104°C, #2 960°C</td>
</tr>
<tr>
<td>17:45</td>
<td>Pyrometer reading in the heat zone, ε=0.9: roof 1243°C, wall 1357 °C</td>
</tr>
<tr>
<td>17:57</td>
<td>Gas suction in the soak zone: 1294°C, 2.1% O₂, 10% CO₂</td>
</tr>
</tbody>
</table>

Table 5.12: Log of furnace conditions for billet test A2-2. (flow rate: x10³ m³/h)

longer than expected. Approximately seven billets were discharged during the delay, over a span of approximately 60 min., before rolling returned to steady-state.

The recorded billet temperature profiles are shown in Figure 5.8 noting that the top thermocouple (#3) was lost 25 min. into the test. During the delay while the instrumented billet was in the heat zone, the measured billet temperatures increased from about 600°C to 860°C. This led to a discharge temperature of about 1260°C that was approximately 100°C hotter than the pyrometer readings. The increase in billet temperatures during the delay is an important finding in terms of developing delay strategies for this type of furnace.
Chapter 5: Characterization of the Billet Reheating Furnace at Company A

Figure 5.7: Measured temperature profiles for billet test A2-2 on Feb. 2, 1995.

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>centreline of billet, 74 mm deep</td>
</tr>
<tr>
<td>2</td>
<td>19 mm from the back face, 80 mm deep</td>
</tr>
<tr>
<td>3</td>
<td>19 mm from the top face, 72 mm deep from the forward face</td>
</tr>
<tr>
<td>4</td>
<td>centreline of billet, 123 mm deep</td>
</tr>
</tbody>
</table>

Table 5.13: Thermocouple layout for the billet test A2-3.

The natural gas and combustion air flow rates recorded during the test are given in Table 5.14. The measurements at 10:25, and prior to the delay, indicate heavy firing in the charge zone but reduced firing in the heat zone. When charging a heat that requires adjustments to the rolls, the practice at the company is to leave a large spacing following the previous heat that is equal to the length of a zone. At 10:25, this spacing was in the heat zone and the firing was thus reduced. The excess air values in the charge, heat and soak zones were -2.0%, 7.0% and 12.8%, respectively.
Chapter 5: Characterization of the Billet Reheating Furnace at Company A

During the delay, the natural gas and combustion air flows were turned down. The natural gas flow rate in the soak zone was reduced from $0.57 \times 10^3$ m$^3$/h to $0.37 \times 10^3$ m$^3$/h, but the tuning of the controllers led to the excess air in the soak zone being 24%. This is an important finding since the excess air lowers the zone temperatures during the delay; but introduces higher oxygen levels in a zone where the steel is the hottest. During the delay, gas suction in the charge zone indicated a gas temperature of 966°C and an oxygen content of 7.2%. The low measurement of 5.0% CO$_2$ is due to the products of combustion being diluted with the excess air. Following the delay, the excess air returns to the steady-state levels of -2.8%, 2.9% and 14.7% in the charge, heat and soak zones, respectively. Gas temperatures in the heat and soak zone were again measured to be high at 1452°C and 1469°C, respectively.

Initially, the optical pyrometer was set to operate at an emissivity of 0.9 that is typical of refractory materials. It was found however that the pyrometer readings would match the plug temperatures at the hot face (about a 40°C decrease) when the emissivity was set to 0.75. In a later

Figure 5.8: Measured temperature profiles for billet test A2-3 on Feb. 3, 1995.
<table>
<thead>
<tr>
<th>Time</th>
<th>Charge zone</th>
<th>Heat zone</th>
<th>Soak zone</th>
<th>Gas</th>
<th>Air</th>
<th>Excess air, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:24</td>
<td>test billet charged</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:25</td>
<td></td>
<td></td>
<td></td>
<td>1.69</td>
<td>0.44</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16.34</td>
<td>4.59</td>
<td>6.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-2.0</td>
<td>7.0</td>
<td>12.8</td>
</tr>
<tr>
<td>10:27</td>
<td>pyrometer reading in heat zone, $\varepsilon=0.9$: roof 1113°C, wall 1238°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:28</td>
<td>gas suction in the charge zone: 1238°C (firing turned down)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>test billet is about 25 billets into the furnace</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:35</td>
<td></td>
<td></td>
<td></td>
<td>0.11</td>
<td>0.076</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.67</td>
<td>1.98</td>
<td>4.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>14.2</td>
</tr>
<tr>
<td>10:40</td>
<td>pyrometer reading in the charge zone, $\varepsilon=0.9$: roof 831°C, wall 949°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:41</td>
<td>gas suction in the charge zone: 966°C, 7.2% $O_2$, 5.0% $CO_2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:50</td>
<td>refractory plug in the soak zone: #3 1077°C, #4 1032°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:08</td>
<td>refractory plug in the heat zone: #1 873°C, #2 884°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:20</td>
<td></td>
<td></td>
<td></td>
<td>0.11</td>
<td>0.076</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.67</td>
<td>1.98</td>
<td>4.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>14.2</td>
</tr>
<tr>
<td>11:32</td>
<td>gas suction in the charge zone: 922°C - furnace still under delay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:35</td>
<td>pyrometer reading in the charge zone, $\varepsilon=0.9$: roof 826°C, wall 904°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>pyrometer reading in the heat zone, $\varepsilon=0.9$: roof 1033°C, wall 1116°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:39</td>
<td>refractory plug in the soak zone: #1 858°C, #2 840°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:45</td>
<td>pyrometer reading in the charge zone, $\varepsilon=0.75$: roof: 875°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11:50</td>
<td></td>
<td></td>
<td></td>
<td>0.11</td>
<td>0.11</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.84</td>
<td>1.98</td>
<td>31.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>27</td>
</tr>
<tr>
<td>11:56</td>
<td>refractory plug in the soak zone: #1 854°C, #2 837°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:15</td>
<td></td>
<td></td>
<td></td>
<td>0.11</td>
<td>0.11</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.86</td>
<td>1.98</td>
<td>3.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>24</td>
</tr>
<tr>
<td>12:19</td>
<td>refractory plug in the soak zone: #1 878°C, #2 823°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:20</td>
<td></td>
<td></td>
<td></td>
<td>1.60</td>
<td>1.55</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15.38</td>
<td>15.46</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-2.6</td>
<td>1.3</td>
<td>517</td>
</tr>
<tr>
<td>12:24</td>
<td>gas suction in the charge zone: 1285°C, 1.0% $O_2$, 10.0% $CO_2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.14: Log file for billet test A2-3. (flow rate: $10^3$ m$^3$/h)
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<table>
<thead>
<tr>
<th>12:25</th>
<th>Charge zone</th>
<th>Heat zone</th>
<th>Soak zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>1.62</td>
<td>1.52</td>
<td>0.56</td>
</tr>
<tr>
<td>Air</td>
<td>15.52</td>
<td>15.43</td>
<td>6.34</td>
</tr>
<tr>
<td>Excess air, %</td>
<td>-2.8</td>
<td>2.9</td>
<td>14.7</td>
</tr>
</tbody>
</table>

12:30 pyrometer in the charge zone, ε=0.75: roof 1178°C, wall 1272°C
heat zone: roof 1342°C, wall 1414°C
soak zone: roof 1447°C, wall 1477°C

12:35 gas suction in the heat zone: 1452°C - probe lost

<table>
<thead>
<tr>
<th>12:35</th>
<th>Charge zone</th>
<th>Heat zone</th>
<th>Soak zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>1.62</td>
<td>1.50</td>
<td>0.56</td>
</tr>
<tr>
<td>Air</td>
<td>15.46</td>
<td>15.38</td>
<td>6.37</td>
</tr>
<tr>
<td>Excess air, %</td>
<td>-3.3</td>
<td>3.9</td>
<td>14.9</td>
</tr>
</tbody>
</table>

12:37 refractory plug in the soak zone: #1 1057°C, #2 855°C

12:45 gas suction in the soak zone (2nd probe): 1469°C, 2.0% O₂, 9.0% CO₂

12:45 refractory plug in the soak zone: #1 1087°C, #2 882°C

Table 5.14: Log file for billet test A2-3. (flow rate: x10³ m³/h)

Plant trial at Company B, it was determined that the two readings matched at an emissivity of 0.9.
It was observed during both trials that the roof of the furnace at Company A is darker in color than
the walls and much darker than the roof of Company B’s furnace. Although difficult to verify, it is
believed that due to a history of leaner combustion in the furnace at Company A, there may have
been some sooting on the furnace roof and this may have affected the surface’s emissivity.

The objective of the fourth billet test (A2-4) conducted on Feb. 4, 1995, was to
characterize another furnace transient during a planned delay. The thermocouple layout is similar
to those used previously (Table 5.15) with the log file for this test given in Table 5.16. Difficulties
were encountered in starting this test because billets were not being produced by the caster at a
fast enough rate to keep up with the mill. The billet yard contained warm billets but the cold, test
billet could not be charged in with these billets since the results would be difficult to interpret.
The test billet was charged at 21:55 with a heat of low carbon billets that had eventually cooled.

The thermocouple profiles shown in Figure 5.9 demonstrate typical heating profiles while
the billet was in the charge zone and prior to the delay. During the delay, the billet continued to
increase in temperature from about 500°C to 750°C, and homogenize to within 30°C by the end of
the delay. As expected, the top and front thermocouples respond the quickest when the firing was
Chapter 5: Characterization of the Billet Reheating Furnace at Company A

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>all thermocouples near the middle of the furnace</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>centreline of billet, 79 mm deep</td>
</tr>
<tr>
<td>2</td>
<td>centreline of billet, 123 mm deep</td>
</tr>
<tr>
<td>3</td>
<td>19 mm below top face, 75 mm deep from the front face</td>
</tr>
<tr>
<td>4</td>
<td>19 mm from front face, 77 mm deep</td>
</tr>
</tbody>
</table>

Table 5.15: Thermocouple layout for billet test A2-4.

turned back up. There were a few undulations in the temperature profiles towards the end of the test and these were due to the numerous adjustments to the firing strategy carried out by the furnace operator that was described earlier. The discharge temperature of the test billet was relatively high at approximately 1260°C because of the continued heating of the billets during the delay.

The gas flow data taken just prior to the delay shows the charge and soak zones being fired heavier than the heat zone, and as described earlier, this is the company practice when changes are required in the mill. During the delay, the soak zone firing was reduced resulting in 17.6% excess combustion air. After the delay at 22:30, the furnace operator returned the charge and heat zones to full firing, but, in anticipation that the billets in the soak zone would be too hot, the firing in this zone remained at a relatively low level. The changes to the firing rates in the soak zone recorded at 23:14, 23:35 and 23:44 represent the furnace operator’s efforts to maintain a consistent billet discharge temperature and, as indicated in the pyrometer temperatures for this period, this approach was successful.

5.5 Summary

Two plant trial campaigns were successful in gaining new insights into the overall operation of the billet reheating furnace at Company A. Some of the key findings include:

(i) The billet reheating furnace at Company A almost entirely operates under transient conditions. The data demonstrate the presence of both long delays, for example due to roll changes in the mill, and short delays, such as the fine-tuning of the current
<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>21:30</td>
<td>plug in the soak zone: #1 1304°C, #2 1121°C</td>
<td></td>
</tr>
<tr>
<td>21:52</td>
<td>plug in the soak zone: #1 1188°C, #2 1110°C soak zone turned off since the high carbon were discharged from the furnace</td>
<td></td>
</tr>
<tr>
<td>21:55</td>
<td>test billet charged</td>
<td></td>
</tr>
<tr>
<td>22:05</td>
<td>Gas, Air, Excess air, %</td>
<td>Charge zone: 1.63, 16.00, -0.4 Heat zone: 1.02, 10.82, 7.5 Soak zone: 0.57, 5.92, 4.6</td>
</tr>
<tr>
<td>22:08</td>
<td>gas suction in the charge zone: 1196°C (delay prevented gas sampling for composition)</td>
<td></td>
</tr>
<tr>
<td>22:15</td>
<td>Delay - blown entry box into R6 - test billet approximately 11 billets into the furnace</td>
<td></td>
</tr>
<tr>
<td>22:30</td>
<td>Gas, Air, Excess air, %</td>
<td>Charge zone: 1.63, 15.77, -1.6 Heat zone: 1.39, 14.61, 6.2 Soak zone: 0.34, 3.43, 70</td>
</tr>
<tr>
<td>23:25</td>
<td>gas suction in the charge zone: 1221°C, 0.9% O₂, 10.0% CO₂</td>
<td></td>
</tr>
<tr>
<td>23:30</td>
<td>plug in the soak zone: #1 1246°C, #2 1129°C - 49 second stroke</td>
<td></td>
</tr>
<tr>
<td>23:35</td>
<td>Gas, Air, Excess air, %</td>
<td>Charge zone: 1.59, 15.72, 0.3 Heat zone: 1.23, 12.66, 4.4 Soak zone: 0.39, 4.45, 15.7</td>
</tr>
<tr>
<td>23:37</td>
<td>gas suction in the heat zone: 1427°C, 1.3% O₂, 10.0% CO₂</td>
<td></td>
</tr>
<tr>
<td>23:44</td>
<td>Gas, Air, Excess air, %</td>
<td>Charge zone: 1.63, 15.83, -1.4 Heat zone: 0.96, 10.08, 6.4 Soak zone: 0.25, 3.51, 45</td>
</tr>
<tr>
<td>23:47</td>
<td></td>
<td>pyrometer reading in the heat zone, ε=0.75: roof 1353°C, wall 1384°C</td>
</tr>
<tr>
<td>00:04</td>
<td>gas suction in the soak zone: 1370°C, 3.5% O₂, 8.0% CO₂</td>
<td></td>
</tr>
<tr>
<td>00:19</td>
<td></td>
<td>gas suction in the flue: 1179°C, 2.5% O₂, 11.0% CO₂</td>
</tr>
</tbody>
</table>

Table 5.16: Log of furnace conditions for billet test A2-4. (flow rate: x10^3 m^3/h)
Figure 5.9: Measured temperature profiles for billet test A2-4 on Feb. 4, 1995.

roll settings, cobbles in the mill, or cooling beds becoming full. The responses to these delays varied among the different furnace operators with some having more success than others in terms of controlling the discharge temperatures.

(ii) In this furnace, the soak zone was used for substantial billet heating instead of temperature homogenization. Under normal firing conditions, this zone was fired at about 15% excess combustion air which introduces high levels of oxygen in a zone where the steel is the hottest and thus encourages surface oxidation.

(iii) For the 0.20 m billets, the average discharge temperatures scanned by the optical pyrometer were about 50°C colder than the measured temperatures, and as much as 100°C for the 0.15 m billets. This difference was attributed to the billet surfaces being quenched in passing through the descaler ahead of the pyrometer.
(iv) The temperature differentials scanned by the billet pyrometer increased with decreasing billet average and minimum temperatures over the east-most stationary beam. This indicates that skidmark severity is a function of billet residence time. The allowable temperature differential is product dependent where, for example, the allowable temperature differential for the high carbon ball stock is lower.

(v) Because the furnace is pushed beyond its designed capacity, fuel consumption per tonne of steel is high. The flue gas temperatures suggest that a significant amount of thermal energy could be recovered using a recuperator.

(vi) During a mill delay when the firing was significantly turned down, the billets continued to increase in temperature. The current delay strategy is therefore focussed on the recovery of the furnace with the charge and heat zones being brought up to steady-state firing and the soak zone firing rate being used to control the billet discharge temperatures.

(vii) During continuous casting, solidification of the steel produces a dendritic grain structure that rejects solute and gives a carbon enriched billet core. The melting temperature of the core is lower than the outer steel because of the higher carbon content. As a result of delay, the measured discharge temperature of a high carbon, 0.20 m billet exceeded 1250°C, and it is possible that the core of this billet had melted.
Chapter 6: Characterization of the Billet Reheating Furnace at Company B

6.1 Furnace Overview

The billet reheating furnace at Company B is similar to Company A’s except that it is larger in size. It is rectangular shaped measuring approximately 7.3 m wide and 23.1 m in length. The inside height is 1.5 m in the charge zone and 0.9 m in the remaining zones. The furnace is fired by natural gas through roof burners arranged in eleven rows with five burners per row (see Figure 6.1). A key difference is that a recuperator with an operating limit of 482°C (900°F) preheats the combustion air to approximately 425°C utilizing the sensible energy contained in the exiting flue gases. A baffle about 0.5 m in height extends from the roof to separate the charge zone and the flue section in an attempt to retain radiative thermal energy within the main furnace chamber.

For control purposes, the burners are grouped into four zones: Zone 1 (charge zone) with twenty burners, Zone 2 (heat zone) with twenty burners, and Zones 3 and 4 (soak zone) with ten and five burners, respectively. Zone 1 is further divided into “a” and “b” sections of ten burners each for the logging of gas consumption. The total firing capacity for each zone is given in Table 6.1. Control of each zone is carried out using thermocouples inserted through the roof that measure an “averaged” temperature of the combustion gases, refractory and charge. Therefore, as indicated in the previous chapter, the furnace set-points are empirical in nature and arrived at through trial-and-error. The company’s furnace practice, including zone set-points and delay strategies, is not well documented relying heavily on the experience of the furnace operator. An optical pyrometer that measures billet temperatures is located after the rougher stand.

The rougher pulpit is located approximately 50 m west of the discharge end of the furnace. An operator, who has control over the zone set-points and billet pacing, is responsible for manually carrying out the first five roughing passes and this practice has evolved from the complex shapes that are rolled in the mill, for example rails and grader blades. In addition to the pyrometer temperatures following the rougher, the operator also uses current roughing conditions to regulate discharge temperatures with colder billets tending to curl upwards and off the table.
Chapter 6: Characterization of the Billet Reheating Furnace at Company B

Figure 6.1: Schematic diagram of the roof of the billet reheating furnace at Company B.
Chapter 6: Characterization of the Billet Reheating Furnace at Company B

<table>
<thead>
<tr>
<th>Zone</th>
<th>No. of burners</th>
<th>Rated burner capacity (BTU/h)</th>
<th>Burner fuel flow rates (m$^3$/h)</th>
<th>Zone fuel flow rates (m$^3$/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>3.85($10^6$)</td>
<td>105</td>
<td>2100</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>2.6($10^6$)</td>
<td>71</td>
<td>1418</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>1.5($10^6$)</td>
<td>41</td>
<td>409</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>2.8($10^6$)</td>
<td>76</td>
<td>382</td>
</tr>
</tbody>
</table>

Table 6.1: Firing capacities for Company B’s billet reheating furnace.

when rolled. Because of the rougher stage, two key aspects of furnace operation result: (i) the pacing rate, and thus mill throughput, depends on the rougher operator successfully completing the first five passes, and (ii) the operator desires maximum discharge temperatures to ensure the roughing is easily carried out.

The company’s main objectives were: (i) increase the furnace throughput for the 0.25 m billets to approximately 100 tonnes per hour from the current 70-75 tonnes per hour, and (ii) reduce fuel consumption for the other billet sizes. The results presented in this chapter will demonstrate that the fine-tuning of the current operation should allow for higher throughputs to be realized as well as the reduced fuel consumption per tonne of steel.

6.2 Overview of the Plant Trial Campaigns

As indicated in Table 4.1, the first plant trial campaign examined the heating of 0.15 m (5 7/8") billets with the processing of 0.19 m (7 5/8") billets being investigated during the second campaign. In both cases, billets were charged on every stroke of 0.27 m (10.5"). The company also processes 0.25 m billets where the reheating furnace is the rate limiting stage for about 40% of the time. Using the same stroke distance, these billets are charged on every second stroke and the billet throughputs would therefore be expected to be lower.

The rougher pulpit data, which was logged to a printer on the hour, consists of: (i) billet throughputs, (ii) gas consumption in each zone, (iii) zone measured and set-point temperatures, and (iv) flue gas, waste gas, and combustion air temperatures. During the second plant trial
campaign, some of this data were additionally recorded on a datalogger and the billet pyrometer was positioned after the descaler. The plant data and the experimental measurements will be used to show the following:

(i) Mill throughput is limited by the roughing stage for both the 0.15 m and 0.2 m billets.

(ii) The furnace frequently operates under transient conditions.

(iii) The billet heating profiles indicate that the soaking times are too long.

(iv) Delays are detrimental to surface properties including surface melting and scaling.

Although similar in design to Company A’s furnace, it will be shown that the control strategy for this reheating furnace is significantly different. A summary of the major findings in this chapter is included at the end.

6.3 Rougher Pulpit Data

The hourly billet throughputs during the first plant trial campaign (0.15 m billets) are shown in Figures D.1-D.5. On Feb. 28, 1994, the hourly billet count was not steady where, for example, the throughput from 8:00 to 9:00 was thirty-nine billets dropping to five billets two hours later. Minor fluctuations in the billet count are due to the roughing stage, however, major deviations are a result of other conditions in the mill including full cooling beds or delays caused by the shipping department. As expected, the total gas consumption, which is also shown in the figure, generally followed the hourly billet production. The loss of data prior to 9:00 was due to the rougher pulpit printer not being turned on.

Data were also lost on March 1, 1994, due to problems with the printer. The available data indicate that, until 19:00, the hourly billet throughput did not exceed thirteen billets because of a
changeover in the mill for a different finished product. During this period, the gas consumption was greater than 650 m$^3$/h and about one third of the full firing levels even though the furnace still contained steel. The hourly billet count for March 2, 1994, depicted fairly consistent billet throughput, at 20-25 billets per hour, and closer correlation with gas consumption. The same general trends were observed for March 3, 1994, and March 4, 1994, noting that further problems with the printer resulted in data being lost from 0:00 to 9:00.

The billet throughput data for the second plant trial campaign is shown in Figures D.6 and D.7. The first billet test conducted during the second plant trial was performed on Feb. 22, 1995, however the rougher pulpit data was not recorded because the printer was again turned off. On Feb. 23, 1995, the hourly billet count varied from a low of 19 billets in the fifteenth hour to 49 billets in the nineteenth hour. The data from the next day indicates relatively steady operation up until 7:00 with 37 to 46 billets rolled in a given hour. Following this steady-state production, two delays occurred in the tenth and sixteenth hours where the billet throughput was zero.

At Company A, the furnace throughput doubled in going from 0.19 m to 0.15 m billets. However, from these data, billet throughput actually increased with the larger billets. During the first plant trial the smaller billets were being rolled into rails which requires more effort on the part of the rougher operator since the piece has to rotated following each pass. On the other hand, grader blades which are essentially flat were being produced during the second trial allowing for higher billet throughputs. In both trials, the billet throughput data clearly demonstrates the furnace operates primarily under transient conditions.

The rougher pulpit data is the only source of natural gas flow data that is separated into each zone. However, since the data is output to the printer on the hour, the firing rates during short furnace upsets cannot be determined. A plot of total gas consumption versus billet count (Figure D.8) shows considerable scatter, but with increasing billet count leading to higher gas consumption. The higher furnace throughputs observed with the 0.19 m (7 5/8") billets during the second trial resulted in more fuel being consumed at approximately 3500 m$^3$/h. From Table 6.1,
Chapter 6: Characterization of the Billet Reheating Furnace at Company B

the maximum firing capacity for the furnace is about 4309 m$^3$/h and about 23% of the total firing capacity remained available. Other than the higher throughputs, there do not appear to be any other differences between the two billet sizes in terms of fuel consumption. Because the throughput is essentially the same, it would be expected that the larger billets would require more fuel and it can therefore be concluded that there is an abundance of combustion energy available. During periods when the billet production is zero, the total fuel consumption was about 750 m$^3$/h or 17% of the total capacity. It is likely that billets in the furnace during these periods would absorb some of the combustion energy and become overheated.

When the natural gas flow into individual zones is examined, the firing practice becomes more apparent. Figures D.9 and D.10 show the burner and total gas consumption for Zone 1, and, as mentioned earlier, this zone is divided into “a” and “b” components for gas consumption monitoring. Both figures indicate that the trend observed with the total gas consumption was also present in Zone 1 where increasing billet throughput led to increased gas consumption. The greatest burner firing rates observed in Zones 1a and 1b were approximately 75 and 85 m$^3$/h, respectively, being at most 81% of the maximum firing capacity at 105 m$^3$/h. The Zone 1 natural gas flow rate when billet production drops to zero is 300 m$^3$/h, which is just under half of the total gas consumption during this turn down period.

For production rates below fifteen billets per hour, the Zone 2 gas consumption (Figure D.11) was fairly constant at about 8 m$^3$/h per burner, or 160 m$^3$/h for the entire zone. Beyond fifteen billets per hour, the gas consumption increases with higher billet throughput. The greatest firing rate that was observed in this zone was approximately 800 m$^3$/h for the 0.15 m billets versus about 1500 m$^3$/h for the 0.19 cm billets. The rated firing capacity in this zone is 1418 m$^3$/h and it is apparent that this zone was sometimes fired at the maximum.

The firing rates in Zone 3 (Figure D.12) did not generally exceed 25 m$^3$/h, or a total zone firing rate of 250 m$^3$/h. The maximum burner capacity for this zone is 41 m$^3$/h for a total of
409 m$^3$/h. This zone is therefore firing at 61% of its capacity and the firing rate is not sensitive to billet size or throughput. Similarly, Zone 4 is fired at 20-30 m$^3$/h per burner or 100-150 m$^3$/h for the zone (Figure D.13). With the maximum burner capacities at 76 m$^3$/h for at total of 382 m$^3$/h, this zone is fired at about 39% of its capacity with the firing rate also not being sensitive to billet size or throughput.

From this data, it is apparent that the majority of furnace control occurs in Zone 1. Zone 2 would only be firing when the demand in Zone 1 became high due to increased tonnage throughputs, which was the case in the second trial. Zones 3 and 4 were not used in the furnace control strategy since the firing in these zones was independent of billet size and throughput. This control strategy results in billets being rapidly brought up to rolling temperatures and, for a plant that is mill limited, produces long soaking times that can lead to scaling and decarburization of the steel. (During both of the trials, the discharged billets were observed to have severe scaling.) For smaller billets with higher surface area to volume ratios, this control strategy might be even more detrimental since these billets heat up more rapidly under the same conditions. With Zones 3 and 4 firing at 61% and 39% of the maximum capacities, respectively, the company's objective of increasing throughput may be realized by fine-tuning the firing strategy.

The heavy firing in Zone 1 results in thermal energy contained in the products of combustion to be quickly transferred to the flue thus reducing the furnace's thermal efficiency. When the flue gas temperatures are plotted against total fuel consumption (Figure D.14), the gas temperatures increase to approximately 800°C with higher fuel consumption up to about 1400 m$^3$/h. These flue gas temperatures were about 400°C colder than what was measured at Company A and this is attributed to significant amounts of leakage air entering the furnace through the charge entrance. The gas temperatures remain near 800°C until a gas consumption of 2000 m$^3$/h and then decrease to about 600°C. The higher flue gas temperatures at the relatively low total natural gas flows of 1400 to 2000 m$^3$/h result from heavy firing during delays in conjunction with the billets gradually increasing in temperature. When the flue gas temperatures are plotted against the Zone 2 fuel consumption (Figure D.15), it is apparent that maximum
temperatures were reached for low firing rates in this zone suggesting that the flue temperatures were primarily influenced by the firing in Zone 1.

The maximum allowable operating temperature of the recuperator is 482°C (900°F) which is controlled by air dilution. The waste gas temperatures therefore leveled off near 425°C for natural gas flow rates exceeding 1500 m$^3$/h as shown in Figure D.16. The combustion air temperatures are correspondingly limited by the recuperator ranging from 375-425°C (see Figure D.17). The leakage air entering the furnace through the charge entrance inadvertently helped to ensure that the flue gas temperatures were not too high.

6.4 UBC Measurements from the First Plant Trial Campaign - March 2-4, 1994

The first plant trial campaign focussed on the measurement of furnace gas temperatures and oxygen contents at the ten locations indicated in Table 6.2 and Figure 6.1. The gas suction pyrometer measurements for March 2, 1994, are given in Table 6.3. The temperatures south of the baffle, which is toward the charge entrance, were 873 and 988°C, or about 50°C higher than the logged flue gas temperatures. However, on the north side of the baffle that faces the main furnace chamber, the gas temperatures were substantially higher at 1192°C and 1175°C. The gas temperatures in the main furnace chamber ranged from 1242°C to 1353°C and are approximately 100°C colder than what was measured at Company A. The oxygen readings in the main chamber vary from 1.5% to 4.3% indicating that the air/fuel ratios at the burners were high and this would also account for the diluted carbon dioxide readings of 8-10%.

The flue gas temperature was measured at 846°C and agrees well with the temperatures recorded south of the baffle and the logged temperatures. The oxygen content for the flue gases was measured at 4.5% further suggesting that leakage air was entering the furnace through the charge entrance. The combustion air temperature of 388°C and waste gas temperature of 421°C are also in agreement with the logged furnace data.

The thermocouple used for the billet test (B1-1) on March 3, 1994, was situated 86 mm
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Table 6.2: Locations of the access ports used for furnace gas temperature and composition measurement.

<table>
<thead>
<tr>
<th>Port</th>
<th>Description</th>
<th>Location (values are relative to discharge end and west side of the furnace):</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>South of baffle</td>
<td>furnace centreline (~19.8 m, 4.17 m)</td>
</tr>
<tr>
<td>2</td>
<td>North of baffle</td>
<td>furnace centreline (~19.2 m, 4.17 m)</td>
</tr>
<tr>
<td>3</td>
<td>Zone 1, row 1</td>
<td>0.13 m south of burner row, 0.41 m east of burner 2 (16.69 m, 3.20 m)</td>
</tr>
<tr>
<td>4</td>
<td>Zone 1, row 3</td>
<td>0.30 m north of burner row, 0.30 m east of burner 2 (12.60 m, 3.10 m)</td>
</tr>
<tr>
<td>5</td>
<td>Zone 2, row 2</td>
<td>0.46 m south of burner row, 0.10 m west of centre burner (10.62 m, 3.15 m)</td>
</tr>
<tr>
<td>6</td>
<td>Zone 3, row 1</td>
<td>centreline, behind burner (3.28 m, 4.17 m)</td>
</tr>
<tr>
<td>7</td>
<td>Zone 4, row 1</td>
<td>centreline, behind burner (0.48 m, 4.17 m)</td>
</tr>
<tr>
<td>8</td>
<td>Flue</td>
<td>centreline of furnace</td>
</tr>
<tr>
<td>9</td>
<td>Combustion air</td>
<td>west-most burner of Zone 1, row 4.</td>
</tr>
<tr>
<td>10</td>
<td>Waste gas</td>
<td>outside stack</td>
</tr>
<tr>
<td></td>
<td>Door 1</td>
<td>1.02 m from discharge end</td>
</tr>
<tr>
<td></td>
<td>Door 2</td>
<td>5.59 m from discharge end</td>
</tr>
<tr>
<td></td>
<td>Door 3</td>
<td>13.21 m from discharge end</td>
</tr>
</tbody>
</table>

depth along the centreline of the billet with the temperature profile recorded during this test shown in Figure 6.2. Two delays at about 100 min. and 132 min. were attributed to a full cooling bed and problems in the shipping department, however, the delay lengths were not logged in the rougher pulpit. The residence time of the test billet was about 165 min. and the centreline discharge temperature was approximately 1200°C.

The gas suction measurements which are given in Table 6.4 were similar to the results from the previous day. During the first delay, the gas temperature north of the baffle (chamber side) decreased to 1070°C while during the second delay the gas temperature in Zone 2 went from 1250°C to 1192°C. Because the gas temperatures do not appreciably decrease during either of the delays, it is likely that the firing was only marginally turned down and this observation is supported by the gas consumption data from the rougher pulpit data that was described earlier.

For the second billet test carried out on March 4, 1994, three thermocouples were installed
Table 6.3: Gas suction pyrometer measurements for March 2, 1994.

at the locations indicated in Table 6.5. From the measured temperature profiles shown in Figure 6.3, the temperatures rapidly increase at a logged time of about 65 min. and this corresponds to the test billet passing underneath the baffle. (The relatively jagged temperature profiles are due to problems encountered with the thermocouple wire and connector plugs that were corrected before the next trials.) Although substantial thermal gradients were developed in billet while in the charge zone, the temperatures become homogenized by the time it reaches the soak zone, after about 100 min. of heating time. It is evident from this test that the current firing strategy produced long soaking times (~70 min.) and this is detrimental to billet quality since it can lead to excessive scaling. These results indicate the Zone 1 firing rate should be reduced since the current firing strategy already provides for adequate soaking times. This would enable other zones to be brought into the control strategy, improve the furnace's thermal efficiency and potentially improve the billet surface quality.
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The results from the corresponding gas suction measurements are shown in Table 6.6. The flue gases were measured at 787°C and, at this temperature, it is again apparent that leakage air was entering the furnace through the charge entrance. The Zone 1 temperatures of 1361°C and 1374°C and Zone 2 temperature of 1258°C were consistent with previous measurements. The oxygen reading of 3.3% in Zone 2 was relatively high and, because this zone is located near the middle of the furnace, it was likely due to high air/fuel ratios. The carbon dioxide readings of 8% in Zone 2 further suggest that the products of combustion were diluted with excess combustion air. Fine-tuning of the air/fuel ratios in all of the zones and reducing the amount of leakage air entering the furnace would significantly improve the current firing strategies allowing for higher tonnage throughputs to be realized.

Figure 6.2: Measured temperature profile for billet test B1-1 on March 3, 1994.

The results from the corresponding gas suction measurements are shown in Table 6.6. The flue gases were measured at 787°C and, at this temperature, it is again apparent that leakage air was entering the furnace through the charge entrance. The Zone 1 temperatures of 1361°C and 1374°C and Zone 2 temperature of 1258°C were consistent with previous measurements. The oxygen reading of 3.3% in Zone 2 was relatively high and, because this zone is located near the middle of the furnace, it was likely due to high air/fuel ratios. The carbon dioxide readings of 8% in Zone 2 further suggest that the products of combustion were diluted with excess combustion air. Fine-tuning of the air/fuel ratios in all of the zones and reducing the amount of leakage air entering the furnace would significantly improve the current firing strategies allowing for higher tonnage throughputs to be realized.
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<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:44</td>
<td>gas suction north of baffle: 1129°C, O\textsubscript{2}: 2.8%, CO\textsubscript{2}: 10%, 12%, 11%</td>
</tr>
<tr>
<td></td>
<td>10:08 1154°C. 10:59: 1214°C. 11:12: 1138°C, O\textsubscript{2}: 1.9%, CO\textsubscript{2}: 12%, 12%.</td>
</tr>
<tr>
<td></td>
<td>11:47 1070°C -delay.</td>
</tr>
<tr>
<td>11:52</td>
<td>test billet charged</td>
</tr>
<tr>
<td>11:59</td>
<td>optical pyrometer on back side of baffle: 771°C</td>
</tr>
<tr>
<td>12:03</td>
<td>optical pyrometer on back side of baffle: 822°C</td>
</tr>
<tr>
<td></td>
<td>12:28 1138°C, billet passing underneath baffle. 12:35 1138°C</td>
</tr>
<tr>
<td>12:55</td>
<td>gas suction Zone 1, row 3: 1225°C. 13:08 1275°C</td>
</tr>
<tr>
<td>13:07</td>
<td>Door 3: wall 1229°C, roof 1173°C</td>
</tr>
<tr>
<td>13:25</td>
<td>gas suction Zone 2, row 2: 1250°C, O\textsubscript{2}: 1.8%, CO\textsubscript{2}: 10%, 8%.</td>
</tr>
<tr>
<td></td>
<td>13:52 1239°C, furnace restarted</td>
</tr>
<tr>
<td>13:39</td>
<td>Door 2: wall 1278°C, roof 1249°C</td>
</tr>
<tr>
<td>14:09</td>
<td>gas suction Zone 3, row 1: 1308°C, O\textsubscript{2}: 2.9%, CO\textsubscript{2}: 8%, 8%</td>
</tr>
<tr>
<td></td>
<td>Door 1: wall 1348°C</td>
</tr>
</tbody>
</table>

**Table 6.4: Log file for billet test B1-1.**

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Location Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>133 mm deep from the top face, 44 mm from the front face</td>
</tr>
<tr>
<td>2</td>
<td>44 mm deep from the top face, 44 mm from the back face</td>
</tr>
<tr>
<td>3</td>
<td>130 mm deep from the top face, over the east most skid</td>
</tr>
</tbody>
</table>

**Table 6.5: Thermocouple layout for billet test B1-2.**
Chapter 6: Characterization of the Billet Reheating Furnace at Company B

Figure 6.3: Measured temperature profiles for billet test B1-2 on March 4, 1994.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:27</td>
<td>Gas suction in the flue: 787°C, O₂: 2.8%, CO₂: 10%, 12%, 11%</td>
</tr>
<tr>
<td>10:49</td>
<td>Gas suction north of baffle: 1066°C, 11:00 1142°C, 11:51 1171°C, O₂: 1.4%, CO₂: 10%</td>
</tr>
<tr>
<td>10:53</td>
<td>Test billet charged</td>
</tr>
<tr>
<td>12:08</td>
<td>Gas suction Zone 1, row 3: 1361°C, 12:22 1374°C, O₂: 0.9%, CO₂: 8%, 8%</td>
</tr>
</tbody>
</table>
| 12:23  | Door 3: wall 1274°C, roof 1209°C  
        | Door 2: wall 1333°C, roof 1295°C                                                   |
| 13:00  | Gas suction Zone 2, row 2: 1258°C, O₂: 3.3%, CO₂: 8%, 8% - probe broke             |

Table 6.6: Log file for billet test B1-2.
6.5 UBC Measurements from the Second Plant Trial Campaign - Feb. 22 - 24, 1995

A primary objective of the second plant trial campaign was to determine whether the heating profiles would be similar for 0.19 m (7 5/8") billets. Since the firing practice had not changed from the previous trial, obtaining billet heating profiles was the primary focus. For the larger billets, the tonnage throughput increased approximately 70% since the billet pacing rate was about the same, and thus the furnace was under heavier demand.

The air/fuel ratios, given in Table 6.7, support many of the observations made from the first trial. Depending on the composition of the fuel, the stoichiometric air/fuel ratio is about 9.5. A ratio of 10.5 corresponds to about 12% excess air which is high, especially when leakage air is present. A better firing strategy would have Zones 2, 3 and 4 fired more leanly to improve the thermal efficiencies in these zones and minimize scale formation. The air/fuel ratio should then be near 10% in Zone 1 to ensure full combustion of the fuel before the furnace gases exit via the flue. The furnace pressure of 1.1 mm water column was approximately half of that at Company A thus increasing the potential for leakage air to enter the furnace.

The first test (B2-1) examined billet heating while the furnace was operating near steady-state. The thermocouple layout, which is given in Table 6.8, was designed to measure billet temperatures along the furnace centreline. The temperature profiles (Figure 6.4) show minimal billet heating until a log time of about 55 min. when the test billet passed underneath the baffle and this phenomena was also observed in the first plant trial campaign. This suggested that leakage air was being drawn into the flue section of the furnace, reducing the overall gas temperatures in this region and lowering the rate of heat transfer to the charge. To verify this, a block of wood that was placed on a trailing billet generated smoke that was drawn horizontally into the furnace until it reached the baffle.

Once the test billet passed underneath the baffle, the top most thermocouple recorded the greatest heating rate. The billet temperatures rapidly increased from 55 min. to about 61 min. after which time the increase in temperatures were more gradual. This period represents the time


**Table 6.7:** Air to fuel ratios for Company B’s reheat furnace (furnace pressure set at 0.9 mm water column and measured at 1.1 mm w.c.)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Air/Fuel Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a and 1b</td>
<td>10.51</td>
</tr>
<tr>
<td>2</td>
<td>10.57</td>
</tr>
<tr>
<td>3</td>
<td>10.53</td>
</tr>
<tr>
<td>4</td>
<td>10.63</td>
</tr>
</tbody>
</table>

**Table 6.8:** Thermocouple layout for billet test B2-1.

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Location Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>95 mm deep from the top face, 21 mm from the front face</td>
</tr>
<tr>
<td>2</td>
<td>95 mm deep from the front face, 19 mm below the top face</td>
</tr>
<tr>
<td>3</td>
<td>173 mm deep from the top face</td>
</tr>
<tr>
<td>4</td>
<td>95 mm deep from the top face</td>
</tr>
</tbody>
</table>

**Figure 6.4:** Measured temperature profiles for billet test B2-1 on Feb. 22, 1995.
Chapter 6: Characterization of the Billet Reheating Furnace at Company B

required for the billet to travel through the remainder of Zone 1 and into Zone 2, noting that the test billets during the first trial also reached rolling temperatures while in Zone 1. The gradual heating in Zone 2 is due to the larger billets requiring heavier firing in this zone which was also observed in the logged furnace data. The discharge temperature was approximately 1265°C and about 50°C hotter than the pyrometer reading. The billet was homogenized in temperature 25 min. prior to being discharged from the furnace suggesting the pacing rate, and thus throughput, could have been increased.

The gas temperatures were similar to those measured during the first trial with Zone 1 at 1287°C and Zone 2 at 1386°C. The control strategy employed by the company, where the firing rates in the soak zone were not responsive to changes in the billet throughput or size, was shown earlier to result in these zones being fired below maximum capacity. This accounts for the lower measured temperature of 1104°C in Zone 3. The oxygen reading on the chamber side of the baffle was 0.5% and the gas temperature was 1204°C. On the flue side, these readings were 2.6% and 949°C, respectively, due to the infiltration of leakage air.

To examine the repeatability of the results from the first test, the second test billet (B2-2), with the thermocouple layout given in Table 6.10, was also carried out while the furnace was operating near steady-state. For this test, the billet pacing rate was 81 s and similar to the pacing rate used by Company A for the 0.20 m billets. The thermocouple profiles, shown in Figure 6.5, again show the sudden increase in heating rates as the test billet passed underneath the baffle. The peaks in the temperature profile of the top face thermocouple occurring at a log time of about 50, 60, 72 and 82 min. correspond to the billet passing underneath each burner row in Zone 1. The residence time was typical for this furnace at 120 min. but still led to a relatively high discharge temperature of about 1280°C. The soaking time was much shorter at about 15 min. confirming that billet processing was relatively steady during this day.

Compared to the previous test, a lower oxygen content was measured on the flue side of the baffle, 1.3%, and was similar to the chamber side at 1.1% (see Table 6.11). Measurements could not be carried out in Zone 1 since the instrumented refractory plug had been inserted into
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<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:10</td>
<td>test billet charged</td>
</tr>
<tr>
<td>16:15</td>
<td>delay in the mill until 16:22</td>
</tr>
<tr>
<td>16:25</td>
<td>gas suction south of baffle: 949°C, 2.6% O₂, 12.0% CO₂</td>
</tr>
<tr>
<td>16:46</td>
<td>gas suction north of baffle: 1204°C, 0.5% O₂, 13.0% CO₂</td>
</tr>
<tr>
<td>17:19</td>
<td>gas suction Zone 1, Row 3: 1287°C, 3.5%O₂, 13.0% CO₂</td>
</tr>
<tr>
<td>17:48</td>
<td>gas suction Zone 2, Row 2: 1386°C</td>
</tr>
<tr>
<td></td>
<td>- gas turned down before composition measurements</td>
</tr>
<tr>
<td>18:00</td>
<td>gas suction Zone 2, Row 2: 1188°C, 0.9% O₂, 13.0% CO₂</td>
</tr>
<tr>
<td>18:24</td>
<td>gas suction Zone 3, Row 1: 1104°C, 0.8%O₂, 13.0% CO₂</td>
</tr>
</tbody>
</table>

Table 6.9: Log file for billet test B2-1.

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>95 mm deep from the top face</td>
</tr>
<tr>
<td>2</td>
<td>176 mm deep from the top face</td>
</tr>
<tr>
<td>3</td>
<td>98 mm deep from the top face, 21 mm from the front face</td>
</tr>
<tr>
<td>4</td>
<td>95 mm deep from the front face, 19 mm below the top face</td>
</tr>
</tbody>
</table>

Table 6.10: Thermocouple layout for billet test B2-2.

this sampling port. However, in the main furnace chamber, the oxygen contents were measured at 2.0% in Zone 2 and 1.2% in Zone 3. These values, that are somewhat high as a result of the air/fuel ratios described earlier, were greater than what was observed during the previous day. While the measurements were being carried out in Zone 3, the discharge door opened and oxygen content in this zone increased to 1.8%. This phenomenon was also observed at Company A stressing the importance of minimizing the time that the discharge door remains open. Compared to the previous day, the gas temperatures were higher in Zones 2 (1412°C versus 1386°C) and 3 (1312°C versus 1188°C) and, in conjunction with the shorter residence times, are an indication of somewhat steadier rolling.

The third test (B2-3) was intended to investigate billet end heating using the thermocouple layout given in Table 6.12. A change in the rolling schedule led to shorter billets being charged
Chapter 6: Characterization of the Billet Reheating Furnace at Company B

Figure 6.5: Measured temperature profiles for billet test B2-2 on Feb. 23, 1995.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:48</td>
<td>refractory plug at Zone 1, Row 3: #1 - 1111°C, #2 - 1077°C</td>
</tr>
<tr>
<td>10:25</td>
<td>test billet charged</td>
</tr>
<tr>
<td>10:30</td>
<td>gas suction south of baffle: 936°C, 1.3% O₂, 11% CO₂</td>
</tr>
<tr>
<td>10:47</td>
<td>refractory plug at Zone 1, Row 3: #1 - 1163°C</td>
</tr>
<tr>
<td>11:03</td>
<td>gas suction north of baffle: 1205°C, 1.1% O₂, 12% CO₂</td>
</tr>
<tr>
<td>11:55</td>
<td>gas suction Zone 2, Row 2: 1419°C, 2.0% O₂, 12% CO₂</td>
</tr>
<tr>
<td>12:22</td>
<td>gas suction Zone 3, Row 1: 1312°C, 1.2% O₂, 12% CO₂ (1.8% O₂ with door open)</td>
</tr>
<tr>
<td>12:40</td>
<td>pyrometer reading: 1121°C (2050°F)</td>
</tr>
</tbody>
</table>

Table 6.11: Log file for billet test B2-2.

and the test billet had to be reduced in length to 4.5 m by cutting the unprepared end. The “centreline” thermocouple was now off-center, but remained far from the stationary beams on the west side of the furnace. The second thermocouple was positioned over the east walking beam and the third thermocouple was situated over the east-most stationary beam. The billet pacing rate
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<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>92 mm deep from top face, centreline of furnace</td>
</tr>
<tr>
<td>2</td>
<td>95 mm deep from the top face, 305 mm from the east end of the billet</td>
</tr>
<tr>
<td>3</td>
<td>81 mm deep from the top face, 152 mm from the east end of the billet</td>
</tr>
</tbody>
</table>


was faster at 71 s because the roughing time for the shorter billets was faster.

The temperature profiles (Figure 6.6) indicate steady-state billet heating with a relatively short billet residence time of 95 min. and a discharge temperature of 1260-1300°C. Similar to the previous tests, the billet appeared to reach rolling temperatures by the time it entered the soak zone. Initially, the thermocouple over the stationary beam heats up at a faster rate because of its close proximity to the end of the billet. With time however, the radiative shielding of the stationary beam led to a reduced heating rate compared to the centreline and walking beam thermocouples. The side burners were not turned off with the shorter billets and the second thermocouple, which is over the walking-beam and otherwise exposed on the bottom face, heated at a faster rate than the centreline thermocouple.

As indicated in Table 6.13, the oxygen contents were: south of the baffle, 5.7%, north of the baffle, 4.0%, Zones 2, 0.8%, Zone 3, 2.0%, and in the flue, 9.2% O₂, in addition to a low measured temperature of 674°C. These measurements further suggest that leakage air infiltrated through the charge entrance and that this was a greater problem with the shorter billets.

The fourth billet test (B2-4) was designed to measure billet heating in Zone 1 during a scheduled short delay due to minor roll gauge changes. The length of this test billet also had to be reduced to 5.5 m by removing approximately 0.36 m on both ends. The thermocouple positioning relative to the furnace wasn’t affected since they were situated along the furnace centreline (Table 6.14). The walking beam stroke interval during this test was 79 s.

Before the delay, the billet temperatures shown in Figure 6.7 were similar to those
Chapter 6: Characterization of the Billet Reheating Furnace at Company B

presented earlier. When the furnace was turned down, the measured temperatures decreased approximately 75°C and was attributed to the Zone 1 controller's derivative component not working correctly. This resulted in high levels of excess combustion air being fired into this zone when the natural gas flow rate was reduced. Following this decrease, the temperatures gradually increased for the next 100 min. as the billet temperatures homogenized to a measured differential of approximately 40°C towards the end of the delay. Ten minutes after the firing was brought back up, a cobble occurred in the mill that produced another delay lasting 20 min. The discharge temperature of the billet was about 1240°C, but due to a residence time in excess of 190 min., extensive scaling was observed on the billets that were being discharged from the furnace.

The flue gas temperature prior to the delay was similar at 914°C but the oxygen content was much lower at 1.5% (Table 6.15) In Zones 2 and 3 the oxygen readings were also lower at 1.7% and 1.8%, respectively, suggesting that the longer billet length of 5.5 m (versus a length of

Figure 6.6: Measured temperature profiles for billet test B2-3 on Feb. 23, 1995.
Chapter 6: Characterization of the Billet Reheating Furnace at Company B

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:30</td>
<td>refractory plug in Zone 1, Row 3: #1 - 1179°C, #2 - 1146°C (during a delay)</td>
</tr>
<tr>
<td>16:00</td>
<td>test billet charged</td>
</tr>
<tr>
<td>16:03</td>
<td>gas suction south of baffle: 905°C, 5.7% O₂, 8% CO₂</td>
</tr>
<tr>
<td>16:15</td>
<td>gas suction north of baffle: 1246°C, 4.0% O₂, 8% CO₂</td>
</tr>
<tr>
<td>16:42</td>
<td>gas suction Zone 2, row 2: 1247°C, 0.8% O₂, 12% CO₂</td>
</tr>
<tr>
<td>17:07</td>
<td>gas suction Zone 3, row 1: 1328°C, 2.0% O₂, 8% CO₂ (2.4% O₂ when door opened)</td>
</tr>
<tr>
<td>17:22</td>
<td>gas suction in the flue: 674°C, 9.2% O₂, 8% CO₂</td>
</tr>
<tr>
<td>18:30</td>
<td>billet pyrometer reading: 1177°C (2150°F)</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 mm deep from the top face, 19 mm from the back face</td>
</tr>
<tr>
<td>2</td>
<td>92 mm deep from the front face, 19 mm below the top face</td>
</tr>
<tr>
<td>3</td>
<td>100 mm deep from the top face, 19 mm from the front face</td>
</tr>
<tr>
<td>4</td>
<td>92 mm deep from the top face</td>
</tr>
</tbody>
</table>

Table 6.14: Thermocouple layout for billet test B2-4.

4.5 m for the third test billet) reduced the amount of leakage air entering the furnace.

6.6 Logged Furnace Data from the Second Plant Trial Campaign

During the second plant trial, furnace data recorded on a datalogger included: (i) zone set-point and measured temperatures, (ii) waste gas, combustion air and flue gas temperatures, (iii) billet count and (iv) total fuel consumption. The readings were taken every five minutes and thus provided greater detail than the rougher pulpit data. Ideally, the natural gas consumption in each zone would have been recorded, however, the total gas usage still provides some insights into the firing of the furnace during delays.

The first test billet, that was charged into the furnace at 16:10 on Feb. 22, 1995, indicated steady-state billet heating. The plots of set-point and measured temperatures for each zone on this day are shown in Figures E.1-E.4. Compared to Company A, the measured zone temperatures
were much closer to the set-point values suggesting the furnace was not pushed hard and the rate limiting step was in the mill. This conclusion agrees with the long soaking times that were measured by the instrumented billets. Seven hundred billets were processed on this day and the throughput was steadier than what was suggested by the rougher pulpit data. Two long delays were recorded at 5:30 and 12:15, lasting forty-five minutes and three hours, respectively. At the start of the first delay, the set-point temperature in Zone 1 was marginally reduced from 1218°C (2225°F) to 1149°C (2100°F). Because the set-point change occurred at the same time that the billet count stopped increasing, this was an unscheduled delay. The fact that the set-point temperature was only reduced by 69°C further indicates that the delay was not expected to be long. The remaining plots for Zones 2-4 show that the set-points in all of the zones were reduced simultaneously, noting that the set-point temperature in Zone 4 was only decreased by 30°C.

During the second delay at 12:15, the set-point temperature for Zone 1 was initially reduced at 10:30 while billets were still being discharged from the furnace, indicating that this
delay was scheduled. The plots for the remaining zones show the set-points having been sequentially reduced in response to each zone having been emptied of billets. With the furnace completely emptied, the set-point temperatures in each zone were 982°C (1800°F) and this likely leads to the 650 m$^3$/h of natural gas that was being consumed even though billet throughput was zero. When the next heat of billets was charged into the furnace, the set-points were increased in a similar sequential manner with Zone 1 brought up to 1210°C at 13:30. During this delay, the flue gas temperatures decreased from about 650°C to 375°C (Figure E.5) while the combustion air and waste gas temperatures decreased to approximately 200°C. Natural gas consumption, which is shown in Figure E.6, was 200 m$^3$/5 min., or 2400 m$^3$/h, following the delay agreeing with the rougher pulpit data.

Two test billets that measured steady-state furnace operation were charged on Feb. 23, 1995, at 10:25 and 16:00. From the zone data given in Figures E.7-E.10, the billet throughput was steady throughout the day with approximately 860 billets being rolled. As before, the measured
zone temperatures closely follow the set-point temperatures for most of the day with relatively few changes to the set-points being made. The flue gas temperatures shown in Figure E.11 range from 600-700°C and led to consistent waste gas and combustion air temperatures of about 400°C. The incremental fuel consumption (Figure E.12) was less steady varying from 150-300 m$^3$ per five minute interval.

The zone data for Feb. 24, 1995, is shown in Figures E.13-E.16. The fourth test billet was charged into the furnace at 14:14 and it can be seen from the billet count profile that the delay began at 14:30. The set-point temperatures for all of the zones were reduced at the same time suggesting this delay was not planned. However, the set-points in Zones 3 and 4 were only marginally reduced since the delay involved a roll change that was not initially expected to be long. As soon as the delay appeared to be longer, the soak zone set-points should also have been lowered. As before, the flue gas, waste gas and combustion air temperatures (Figure E.17) correspondingly decreased when the firing was turned down.

6.7 Pyrometer Data Recorded During the Second Plant Trial Campaign

During the second plant trial, an optical pyrometer was moved from a location after the roughing stands to a position following the descaler. The pyrometer had a slow scanning frequency of about 1 Hz giving only three to five readings per billet. From 17:00 to 18:30 on Feb. 22, 1995, the billet temperatures ranged from 1150°C to 1270°C (Figures F.1) and these fluctuations would produce variations in the physical properties in the finished product. The higher temperatures at 17:30 are a result of the billets in the soak zone overheating during the delay and, given that the pyrometer measures a lower temperature because of the descaler, the billet temperatures likely exceeded 1300°C.

The pyrometer data from Feb. 23, 1995, (Figure F.2) shows consistent billet discharge temperatures in the range of 1125-1225°C with two exceptions. From 4:30 to 5:50, the billet temperatures were significantly colder varying from 1080°C to 950°C. At these low temperatures, the billets may have required higher rolling forces, however, adjustments to the heat and soak
zone firing rates indicate that the colder discharge temperatures were intended. After 11:00, the billet temperatures exceeded 1250°C and it is again likely that the actual billet temperatures exceeded 1300°C.

6.8 Summary

The results from the plant trial campaigns indicate several areas where furnace performance could be improved to achieve higher tonnage throughputs, which was one of the primary objectives of the company. The major findings are briefly summarized as follows:

(i) In both trials, the rate limiting step in terms of production was the roughing stage. As a result, the pacing rate for both billet sizes was the same even though the tonnage throughputs were significantly different. Minor fluctuations in billet throughput were due to the roughing practice whereas the longer delays generally resulted from full cooling beds or problems in the shipping department. The reheating furnace was not under heavy demand during either plant trial campaign and the measured zone temperatures remained close to the set-point values.

(ii) The thermal efficiency of the reheating furnace would be improved with tighter control of the burner air/fuel ratios and reducing the amount of leakage air entering the furnace at the charge entrance. In a well operating furnace, leakage air is minimized, and the total furnace pressure increased, with the proper installation of mesh curtains at the charge entrance. This would enable the subsequent fine-tuning of air/fuel ratios in each zone in order to define the new set-points to achieve the desired billet heating profiles.

(iii) The furnace firing strategy was biased towards Zones 1 and 2. The rapid heating followed by long soaking times is fuel inefficient since the products of combustion have relatively short residence times in the furnace. At higher temperatures for longer times, the steel is more susceptible to oxidation and several billets were observed to have severe scaling problems, especially as a result of mill delays. During steady-state operation, the firing rate in Zone 1 should be reduced in favor of Zones 3 and 4 to produce shorter soaking times. The firing in all of the zones should be reduced further during delays, as is the practice at Company A, since the measurements indicate
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the billets continue to increase in temperature. This would be particularly important if the zone firing ratios and leakage air adjustments that were described earlier are carried out.
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In terms of energy effects, a mathematical model of a reheat furnace must account for the energy generated by combustion, the transfer of sensible energy in the products of combustion, the thermal energy radiated from the furnace gases to the charge and the heat lost through the furnace refractory. Further, it is evident from the plant trial campaigns that billet furnaces are seldom in steady-state and a transient formulation must therefore account for adjustments to the fuel firing rate and changes to the billet pacing rate, such as during delays. The model developed in this study incorporates three significant features:

(i) a three-dimensional formulation produces a global model of the furnace where energy balances are satisfied directly,

(ii) gas temperatures are calculated from firing conditions and radiative heat transfer, and,

(iii) a transient formulation enables delay strategies to be developed.

As indicated earlier, the reheating furnaces of both companies are similar in design and a schematic diagram of Company A's furnace is presented in Figure 7.1. The furnaces are top-fired through numerous burners with most of billet heating occurring on the top face. The walking beam design, however, introduces gaps between the charge elements that also influence the rate at which billets are brought up to rolling temperatures. The floor of the furnace consists of a hearth situated approximately 0.12 m below the billets and this makes characterization of the heat transfer in this region difficult. The major assumptions employed in the model are as follows.

(i) The numerous roof burners distribute the combustion energy over an entire control zone. They are designed to produce short flame lengths that will not impinge on the steel and produce relatively less intense mixing and recirculation. As a result, the products of combustion are assumed to travel through the furnace in a manner where
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Figure 7.1: Schematic representation of the steel reheating furnace at Company A.

the extent of back-mixing is relatively small.

(ii) Described in detail later, the radiative characteristics of the furnace atmosphere can be represented by a clear-plus-grey-gases model.

(iii) Because the dimensions between and underneath the billets are relatively short, heat transfer within the gaps is governed by radiation with both convection and the influence of an intervening atmosphere being neglected.

Reheating furnaces are usually controlled by zone thermocouples inserted through the roof or walls and the measured temperatures represent some “average” between the furnace gas, refractory and charge. It is difficult to develop a mathematical model that can predict the temperatures measured by these zone thermocouples. Additionally, the optical pyrometer measurements that are used to monitor billet discharge temperatures also present problems for the model because of the quenching of the billet faces while passing through the descaler. It can therefore be concluded that fuel flows (natural gas and combustion air) and billet pacing rates are the key operating parameters that link the model predictions with actual furnace operation.
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7.1 Selection of a Modelling Methodology

Reheating furnaces have generally been modelled by “marching schemes”, “axial” formulations or “global” formulations. With marching schemes, the furnace is modelled as a series of transverse slices, with respect to the furnace axis, that are evaluated in succession. The final solution is obtained when the error in the overall energy balance for the furnace is below a specified value. The advantage of marching schemes is that they are relative undemanding of computation time and memory. However, they are not suitable for transient furnace modelling. Axial formulations examine charge heating along the furnace centreline. Although they can be formulated for simulating furnace transient behavior, they ignore wall losses and skidmark generation, which has already been shown to be an important process variable at one of the companies in this study. Global models are of greater complexity and require longer execution times, but can readily incorporate radiative exchange in three-dimensions in addition to a transient formulation. With these advantages and the increasing availability of computing power, a greater number of these models are being developed.

Several methods for determining radiative heat transfer have been applied to the reheat furnace. The flux method superimposes a nodal grid over the domain to be solved for (i.e. the furnace chamber) and a radiative balance surrounding each differential volume is then solved.\textsuperscript{59,60} It is assumed that radiative exchange is limited to bounding gas volumes or surfaces and this tends to overly simplify the radiative characteristics of the furnace gases. An advantage of this technique is that nodal discretization permits a coupling to fluid flow models. In the Monte Carlo method, an energy ray having a random orientation is emitted from an arbitrarily chosen surface.\textsuperscript{61-65} As it passes through the enclosure, it is gradually dissipated by absorption in the gas phase and at each surface it comes into contact with. For a large furnace, the tracking of a significant number of energy bundles is required to adequately describe the radiative exchange. The Monte Carlo method is capable of simulating radiative heat transfer in irregular geometries, but increases in complexity when radiatively participating furnace atmospheres are considered.\textsuperscript{50}

In this study, radiative exchange was characterized using the Zone Method since it had
been successfully used in the modelling of gas-fired furnaces. With this technique, the furnace chamber is discretized into a large number of “isothermal” gas and surface zones and the furnace gases are modelled as a sum of grey gases. This approach enables the problem to be divided into geometric terms and temperature dependent terms. For a given furnace geometry and billet configuration, the geometrical terms (direct exchange areas) are calculated only once and then saved. A furnace model then repeatedly uses these data to evaluate the radiative exchange for different operating conditions, such as changes in the firing rates during delays.

### 7.2 Representation of the Furnace Atmosphere using a Clear-Plus-Grey Gases Model

A key element in accurately calculating radiative heat transfer is the ability to simulate the radiative properties of the furnace atmosphere. In the Zone Method, this is accomplished using a clear-plus-grey gases model where the emissivity and absorptivity are described by:

\[
\varepsilon = \sum_{i=0}^{N} a_{e,i}(T_g) \left[ 1 - e^{-k_g l} \right] \\
\alpha = \sum_{i=0}^{N} a_{\alpha,i}(T_g, T_s) \left[ 1 - e^{-k_g l} \right]
\]

where \(N\) is the number of grey gases and \(i=0\) is the clear gas. In this study, the emissivity and absorptivity weighting coefficients, \(a_{e,i}\) and \(a_{\alpha,i}\), for a clear-plus-three-grey gases model were used. Expressed as polynomial functions of gas and surface temperatures, they were fitted to a 2:1 \(\text{H}_2\text{O}:\text{CO}_2\) mixture which is produced from the combustion of methane (the primary component of natural gas). The corresponding extinction coefficients, \(k\), are 0 (clear gas), 0.4201, 6.203 and 131.9 atm\(^{-1}\)m\(^{-1}\); opacity increasing with each grey gas.
7.3 Evaluation of the Radiative Exchange Factors Incorporating Gas Radiation

In the Zone Method, the furnace chamber is discretized into a finite number of volume zones and the perimeter, which consists of the roof, walls and charge, is divided into surface zones. Assuming these zones are isothermal and the furnace atmosphere can be represented by a mixture of grey gases, the radiative exchange between these zones for a given grey gas is then:

\[ q_{A_i \leftrightarrow A_j} = (E_i - E_j) \int_{A_i, A_j} \frac{\cos \theta_i \cos \theta_j}{\pi r^2} \tau_{i \leftrightarrow j} dA_i dA_j = \bar{s}_{i j} (E_i - E_j) \]  \hspace{1cm} (7.3)

\[ q_{A_i \leftrightarrow V_j} = (E_i - E_j) \int_{A_i, V_j} \frac{\cos \theta_i K_j}{\pi r} \tau_{i \leftrightarrow j} dA_i dV_j = \bar{s}_{i j} g_j (E_i - E_j) \]  \hspace{1cm} (7.4)

\[ q_{V_i \leftrightarrow V_j} = (E_i - E_j) \int_{V_i, V_j} \frac{K_i K_j}{\pi r^2} \tau_{i \leftrightarrow j} dV_i dV_j = g_i g_j (E_i - E_j) \]  \hspace{1cm} (7.5)

The absorptivity term, \( \tau_{i \leftrightarrow j} \), is defined as:

\[ \tau_{i \leftrightarrow j} = e^{-Kl} \]  \hspace{1cm} (7.6)

where \( K \) is the product of the extinction coefficient and the combined partial pressures of carbon dioxide and water vapor in the furnace atmosphere (~0.24 for the combustion of natural gas).
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The terms $s_i s_j$, $s_i g_j$ and $g_i g_j$ are defined as the direct exchange areas and since they are independent of temperature, they are calculated only once and the results saved. The number of calculations is reduced by taking into account reciprocity: $s_i s_j = s_j s_i$, $s_i g_j = g_j s_i$ and $g_i g_j = g_j g_i$. Provided that the geometry is fully enclosed, the direct exchange areas have the following identities for each grey gas,

$$\sum_{j=1}^{N_s} s_j s_i + \sum_{j=1}^{N_g} g_j s_i = A_i \quad (7.7)$$
$$\sum_{j=1}^{N_s} s_j g_i + \sum_{j=1}^{N_g} g_j g_i = 4 K V_i \quad (7.8)$$

These identities are used to assess the accuracy of the numerical procedure that is used to evaluate the direct exchange areas.

Because of the separation distance, $r$, in the exponential term in Eqs. (7.3), (7.4) and (7.5), these equations cannot be readily simplified and numerical techniques are required. Hottel replaced the integrals with summations where, for example, the surface-surface direct exchange areas are calculated by

$$s_i s_j = \sum_{A_i} \sum_{A_j} \cos \theta_i \cos \theta_j \frac{\cos \theta_i \cos \theta_j}{\pi r^2} \Delta A_i \Delta A_j \quad (7.9)$$

The accuracy of the integration improves with increasing sub-divisioning; however, the solution time increases exponentially. As a result of this trade-off, Eqs. (7.7) and (7.8) are satisfied to
within a specified accuracy where, for example, 2% was employed by Barr.\textsuperscript{43} Another approach is to average the influence of numerous rays that leave a random point on one zone and arriving at another random point on the other zone. The direct exchange areas, again taking the surface-surface direct exchange area calculation as an example, are then evaluated by

\[ s_{i,j} = \frac{1}{N} \sum_{n=1}^{N} \left( \frac{\cos \theta_{i,n} \cos \theta_{j,n}}{\pi r_{i,n}^2} \right) A_i A_j \] (7.10)

where \( N \) is the total number of rays. The computational time required for the same accuracies was reduced by about 20% since this method doesn’t require the additional effort associated with subdividing a zone.

The direct exchange areas do not take into account reflections within the furnace. For a surface zone shown in Figure 7.2, a fraction of the incident flux density, \( H \), is reflected back into the chamber. The leaving flux density is comprised of an emitted flux and this reflected component, or

\[ W = \varepsilon E + \rho H \] (7.11)

Since the incident flux density on a given surface is the sum of energy fluxes radiated to it from all of the gas and surfaces zones within the enclosure, the following substitution is made

\[ W_i = \varepsilon_i E_i + \rho_i \left[ \sum_{j=1}^{N_s} s_{i,j} W_j + \sum_{j=1}^{N_g} g_{i,j} s_{i,j} E_{g,j} \right] / A_i \] (7.12)

Upon rearrangement, this equation is then expressed in matrix form as
where $\delta_{ij}$ is the Kronecker delta. Described in greater detail in [40], a unit emissive power is assigned in succession to each surface and gas zone, $i$, and the corresponding leaving flux densities, $iW_j$, at $j$ are then evaluated. From these values, the total exchange areas, which now account for reflections, are obtained from:

$$
\sum_{j=1}^{N_r} \left( \frac{A_j}{s_j} - \delta_{ij} \rho_j \right) \{iW_j\} = \left\{ -\frac{A_i \varepsilon_i E_i}{\rho_i} \sum_{j=1}^{N_g} g_j s_j E_{g,j} \right\}
$$

(7.13)

$$
\overline{S_i S_j} = \overline{s_j S_i} = \frac{A_i \varepsilon_i}{\rho_j} (iW_j - \delta_{ij} \varepsilon_j)
$$

(7.14)

$$
\overline{G_i S_j} = \overline{s_j G_i} = \frac{A_j \varepsilon_j}{\rho_j} iW_j
$$

(7.15)

$$
\overline{G_i G_j} = \overline{g_j G_i} = \overline{g_i g_j} + \sum_{k=1}^{N_s} s_k g_{ii} W_k
$$

(7.16)
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For a black body emissive power of unity, the sum of energies incident on that surface must also be unity. Therefore, the following identities exist:

$$\sum_{j} S_j S_l + \sum_{j} G_j S_l = A_i e_l \quad (7.17)$$

$$\sum_{j} G_j G_i + \sum_{j} S_j G_i = 4K_i V_i e_{g,i} \quad (7.18)$$

These identities are used to assess the relative errors of the total exchange area calculations.

Some effort has been focussed at developing faster schemes for directly calculating the total exchange areas. These schemes, however, have not been widely applied to engineering problems and the approach developed by Hottel described above was used in this study. A computational flow chart summarizing these calculations is given in Figure 7.3. The total exchange calculations are performed once and then saved for each configuration including: furnace height, width and length, billet height, width and length, and gap size.

7.3.1 Furnace Discretization

A schematic diagram depicting the typical discretization of Company A's furnace is shown in Figure 7.4. For the furnaces in this study, the mathematical model can be simplified by taking into account the symmetry along the centreline axis of the furnace. To account for the energy released from combustion, a gas zone extending from the furnace roof to the top of the billets is assigned to each burner. Again taking symmetry into account, this produces 11 rows by 2 burners for a total of 22 gas zones. In addition, the region between the end row in the charge zone and the flue is assigned 2 gas zones and the flue region itself is further divided into 2 gas zones. This produces a total of 26 gas volumes. In comparison, Company B's furnace has 11 rows of
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Start

Read in furnace geometry
Read in burner geometry
Read in billet dimensions and gap size
Discretize furnace

Calculate surface-surface direct exchange areas for clear and 3 grey gas components

Calculate surface-gas direct exchange areas for 3 grey gas components

Calculate gas-gas direct exchange areas for 3 grey gas components

Calculate total exchange areas to include reflections within the furnace

Evaluate errors in direct and total exchange areas

End

Figure 7.3: Computational flow diagram for the evaluation of the direct and total exchange areas.
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Figure 7.4: Schematic diagram depicting the discretization of Company A’s furnace: (a) 26 gas zones and (b) 323 surface zones.
burners and 5 burners per row and is discretized with 3 gas zones across the furnace width giving 39 gas zones in total. In this case, the burners along the centreline are fired with half of the actual fuel because of the furnace symmetry. This discretization allows for temperature variations in the furnace gases in both the longitudinal and transverse directions to be evaluated.

The gas volumes for both furnaces are bounded on the top by the roof giving 26 and 39 surface zones, respectively. In both cases there are 13 gas zones along the symmetry plane and 13 gas zones along the wall. The number of surface zones on the charge zone end wall and soak zone end wall correspond to the number of gas zones across the half-width of the furnace, being 2 and 3, respectively. The refractory is therefore defined by 56 and 71 surface zones for Company A’s and Company B’s furnaces, respectively, and these are generally not changed.

The base of the combustion chamber is comprised of billets, gaps and a “hearth channel” between the ends of the billets and the wall. The billets, and gaps, are divided along their length to correspond to the number of gas zones across the half-width of the furnace. The widths of these surface zones equal the billet and gap widths, respectively. The exposed hearth between the ends of the billets and the furnace wall are discretized to correspond with the gas volumes along the wall. For Company A’s furnace, the processing of 0.15 m billets on a 0.27 m stroke leads to a total of 267 zones for the base of the combustion chamber (Table 7.1).

The storage of the direct and total exchange area arrays requires a considerable amount of computer memory. For example, a matrix of 300 zones x 300 zones for 4 grey gases represents a total of $3.6(10^5)$ numbers. Given that the accuracies are within about 2%, the direct and total exchange areas were therefore stored as single precision values (4 bytes of memory) and the memory requirement for each array is then 1.4 MB. With an Intel 486-DX266, the direct and total exchange area calculations for Company A’s furnace required approximately half a day to obtain the accuracies described above.
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| Furnace dimensions (width x height x length), m | 5.4 x 0.91 x 17.4 |
| Discharge ramp distance inside of the furnace, m | 0.5 |
| Stroke distance, m | 0.267 |
| Discretization (with symmetry) | |
| total number of surface zones: | 323 |
| symmetry plane | 13 |
| bottom - billets | 126 |
| bottom - gaps | 128 |
| bottom - hearth channel | 13 |
| side wall | 13 |
| roof | 26 |
| charge end wall | 2 |
| soak end wall | 2 |
| total number of gas volumes: | 26 |
| Gas temperature, °C | 25.0 |
| Combustion air temperature, °C | 2.0 |
| Ambient temperature, °C | 25.0 |
| Billet dimensions (width x height x length), m | 0.152 x 0.152 x 4.78 |
| Billet nodal density (width x height x length) | 9 x 9 x 41 |
| Billet initial temperature, °C | 2.0 |
| Hearth dimensions (length x thickness), m | 17.4 x 0.3 |
| Hearth nodal density (length x thickness) | 601 x 7 |
| Hearth block height, m | 0.060 |
| Wall thickness, m | 0.3 |
| Wall nodal density | 7 |
| Roof thickness | 0.3 |
| Roof nodal density | 7 |

Table 7.1: Baseline modelling parameters for the processing of 0.15 cm billets at Company A (excluding thermophysical properties).

7.4 The Transient, Furnace Model

With the geometrical properties of the furnace having been incorporated into the total exchange areas, a separate model is used to calculate radiative exchange within the furnace and simulate transient phenomena. A computational flow diagram for the furnace model is shown in Figure 7.5 from which two distinct processing loops can be identified. An inner loop represents the iterative solution of the gas temperatures that is required since radiative heat transfer is proportional to temperature to the fourth power. The outer loop is associated with the time step during which the chamber, billet/gap, hearth and wall/roof modules are executed in succession.
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Details related to the execution of the model, RFSIM, are given in Appendix G.

7.4.1 The Chamber Module

The total exchange areas combine with the emissivity and absorptivity weighting coefficients of the furnace atmosphere model to produce directed exchange areas. For example, surface-surface radiative exchange is expressed as

$$ Q_{A_i \leftrightarrow A_j} = E_i \overrightarrow{S_i S_j} - E_j \overrightarrow{S_j S_i} $$

(7.19)

where

$$ S_i S_j = \sum_n [a_{s,n}(T_i)] (\overrightarrow{S_i S_j})_n \quad \text{and} \quad \overrightarrow{S_j S_i} = \sum_n [a_{s,n}(T_j)] (\overrightarrow{S_j S_i})_n $$

(7.20)

Similar expressions are produced for the gas-surface and gas-gas exchange. The gas temperatures are then iteratively solved to satisfy the following energy balances for each gas zone:

$$ \sum_{j=1}^{N_g} \overrightarrow{S_j G_i E_j} + \sum_{j=1}^{N_g} \overrightarrow{G_j G_i E_j} - \sum_{n} 4 a K_n V_n E_{i,n} + q_{enth} + q_{comb} = q_{acc} $$

(7.21)

where $q_{comb}$ is the energy release rate due to combustion, $q_{enth}$ is the rate of decrease in sensible enthalpy of gas flowing into and out of the zone and convection from any contiguous surfaces, and $q_{acc}$ is the transient term for the rate of storage in the zone. Because of the low thermal capacity of the furnace gases and high gas velocities, the accumulation term is negligible compared to the combustion and sensible enthalpy terms. Once the gas temperatures have been obtained, the heat fluxes to the surface zones are then evaluated from the energy balance:
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Figure 7.5: Computational flow diagram for the reheating furnace model.
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\[
\sum_{j=1}^{N_{\text{g}}} S_j \dot{S}_j E_j + \sum_{j=1}^{N_{\text{g}}} G_j \dot{S}_j E_j - A_i E_i + h_i A_i (T_g - T_{s,i}) = q_{\text{net},i}
\]  

(7.22)

7.4.2 Combustion and Sensible Energy

The energy released by combustion is treated by the model as a volume phenomenon noting that one gas zone is assigned to each burner during the discretization of the furnace. Of the energy generated by combustion, some will raise the sensible energy of the products of combustion but the remainder radiates to neighboring gas zones, billets, and furnace refractory (see Figure 7.6). The firing module is configured for a variety of fuel mixtures including natural gas, combustion air, pure oxygen, and leakage air, provided the combustion reactions can be represented by the equations given in Table 7.2. Because the direct exchange areas depend on the combined partial pressures of carbon dioxide and water vapor, they should be re-evaluated whenever the fuel mixture is changed. However, this is impractical because of the computing time that would be required and minor changes to the partial pressures have been neglected.

The majority of the reheating furnace models simplify the movement of the furnace gases by assuming well-stirred, plug flow zones.\textsuperscript{43,46,49} Rhine and Tucker have used physical models to characterize gas flow movement and the effects of flames within a furnace.\textsuperscript{65} Detailed computational flow models for a reheating furnace have been developed by Matsunaga and Hiraoka\textsuperscript{72} and by Rubini et al\textsuperscript{73}, however, they were not coupled to a thermal model because of the high processing requirements.

The furnaces in this study are fired by several, evenly spaced roofs burners that are designed to generate short length flames that will not impinge on the steel surface. The products of combustion should therefore be well distributed throughout each control zone and recirculation effects should be small. For these reasons, the movement of furnaces gases in this model is represented by plug flow. At the beginning of this study, the practice of closing off burners for smaller billets was carried out at Company A; however, this is no longer necessary with the
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Figure 7.6: Energy distribution within a gas zone.

The enthalpy increment for the i'th component of the furnace gas is given by

\[ h_{i,T} = \frac{1}{C_p} \int_{298K}^{T} dT \]  

(7.23)

and the change in sensible energy across a gas zone is then

\[ q_{enth} = \left( \sum_{i}^{N} n_i h_i \right)_{out} - \left( \sum_{i}^{N} n_i h_i \right)_{in} - \left( \sum_{i}^{N} n_i h_i \right)_{fuel} \]

(7.24)

where N represents the number of gas species that are present in the products of combustion (Table 7.3). The specific heat data, which are expressed as polynomials of temperature, are inte-
Table 7.2: Reactions considered in the combustion module.\textsuperscript{56}

At the high operating temperatures of a reheating furnace, convective heat transfer contributes only a small amount to the total heat transfer to the steel. Stry and Felske\textsuperscript{44} calculated this to be approximately 5% of the total heat transfer whereas Barr\textsuperscript{43} suggests a value of 10%. It is therefore sufficient to use the Dittus-Boelter relationship\textsuperscript{76},

\[
Nu = \frac{hk}{D_H} = 0.023 Re^{0.8} Pr^{0.4} \tag{7.25}
\]

to calculate heat transfer coefficients between the furnace gases and the roof, walls and top face of the billets. Thermophysical properties for typical furnace gases required in Eq. (7.25) were obtained from Rhine and Tucker and are expressed as polynomial functions of temperature.\textsuperscript{65} Gas velocities and heat transfer coefficients for each gas zone are calculated assuming plug flow and for the furnaces in this study, the products of combustion travel towards the charge end and thus the gas velocities are highest at this end. Using the above relationship, the calculated convective heat transfer coefficients for Company A's furnace were determined to be about 10.2 W/m\(^2\)-K in the soak end and approximately 100 W/m\(^2\)-K in the charge end.

7.4.3 Numerical Solution of the Energy Balances

The most critical component of the chamber module is the solution of the gas zone energy


balances given in Eq. (7.21). Finding a unique set of gas temperatures that satisfy the energy balances is difficult because the emissive black body energy is a function of temperature to the fourth power and both the gas weighting coefficients and enthalpies are polynomial functions of temperature. Numerical methods are therefore required and in this study a Newton-Raphson iterative scheme developed at the Argonne National Laboratories is employed. With an initial guess supplied for all of the gas zone temperatures, the solver applies a user specified temperature increment to each zone in succession to examine its sensitivity to the energy balances. It then employs a “steepest descent” technique in order to minimize the errors in the gas zone energy balances to within a user specified tolerance. Following the initial series of iterations equal to the number of gas zones, the final solution is obtained in 3-5 iterations. Approximately 40% of the total computing time is associated with the solution of the gas temperatures.

Once the gas zone energy balances have been satisfied, the surface zone energy balances are then evaluated using Eq. (7.22) to produce the heat fluxes to the roof, walls, charge and gaps. For the remainder of the time step loop, these heat fluxes are used in the respective modules generating new surface temperatures which are then utilized by the chamber module for the next time step.
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7.4.4 The Implementation of Dynamic Firing

As part of the operating practice, natural gas and combustion air flows are regularly adjusted in response to mill delays as well as the charging and emptying of the furnace. This is implemented in the model via a control file, FIRING.DAT, that is composed of several data “packets”. A single packet contains the firing rates for each of the fuels in each of the control zones. It is applied for a specified duration and by adding several of these packets in succession, dynamic firing is approximated. For example, a schematic diagram demonstrating how firing may be represented for a single fuel is given in Figure 7.7. For the purposes of developing delay strategies, a typical simulation consists of five stages.

(i) **Furnace preheating**: Light firing is applied to bring the furnace refractory up to operating temperatures.

(ii) **Charging**: Control zones are brought up to steady-state firing in a staggered manner as each zone is filled with billets. The model can be used to examine different charging strategies, such as the application of faster pacing rates to quickly fill the furnace. However, since a primary objective of this study was to assess the operation of the furnace during mill delays, a detailed analysis of different charging strategies has been left as future work.

(iii) **Steady-state operation**. This is achieved when the differences in billet discharge temperature are below a specified value, i.e. 1°C. Although reheating furnaces are seldom in steady-state operation, this stage provides a starting-point for comparing alternative delay strategies. The model has the option of using previously calculated steady-state gas, refractory and billet temperatures therefore bypassing the preheat and charging stages.

(iv) **Delay**. During this stage, the firing in the furnace is significantly turned down.
For most furnaces, the development of delay strategies is based on analyzing stages iv and v. However, it was shown in the previous chapters that the delay strategies for the furnaces in this study already incorporate turning down the firing during the delay and even with this adjustment, the billets continued to increase in temperature during the delay. The development of delay strategies is therefore focussed on the recovery of the furnace, stage v.

7.4.5 Heat transfer in the Gap between Billets

The spacing between elements of the charge, or “gap”, influences the rate the steel is brought up to rolling temperatures. The domain considered for the gap module is shown in Figure 7.8. In a similar manner to Hottel and Sarofim\(^{40}\), Barr\(^{43}\) and Li \textit{et al}\(^{48}\), the heat flow calculated in the chamber module crosses a fictitious plane, “2”. Because the dimensions of the gap are relatively small, it is assumed that the furnace atmosphere does not affect radiative heat
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transfer. The flow of furnace gases into the gap, and underneath the billets, is difficult to calculate and it is likely that the array of billets at the base of the combustion chamber restricts the furnace gases from penetrating into the gaps. The density of the "colder" gases in the gap may also limit the mixing of the gases in this region with the chamber gases. Heat transfer within the gap is therefore simplified to radiative heat transfer, since it generally dominates over convection at higher temperatures.

View factors within the gap are calculated by the cross-string method. In addition to the heat flux across the top boundary of the gap, the following boundary conditions are also used: (i) average billet face temperatures on boundaries 1, 3, 4 and 10, (ii) average hearth temperatures for boundaries 6, 7 and 8, and (iii) no heat flow across boundaries 5 and 9 assuming local symmetry with neighboring gaps. With these boundary conditions, the distribution of the entering heat flux to the remaining boundaries can be evaluated ensuring that energy is conserved within the gap.

7.4.6 Heat Transfer in the Steel - The Billet Module

Heat transfer in the gap is solved in a two-dimensional plane that is perpendicular to the billet axis and parallel to the furnace axis. Other phenomena, including the effects of the stationary beams and the end heating of the billets, require the billets to be modelled in the remaining orientation (transverse to the furnace axis) as well. Heat conduction in the billets is therefore solved in three dimensions based on the following governing equation

$$\frac{\partial}{\partial x}\left(k_{st}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{st}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{st}\frac{\partial T}{\partial z}\right) = \rho_{st}C_{p, st}\frac{\partial T}{\partial t}$$ (7.26)

In the billet module, $x$ is defined as the direction in the billet width, $y$ is in the direction of the billet height and $z$ is in the direction of the length of the billet (see Figure 7.9). The origin of the billet is situated along the symmetry plane since the length of the billets can be changed.
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The billet temperatures are evaluated using an Alternating-Direction, Implicit (ADI), finite-difference technique written for three-dimensions. This technique divides the time step by the number of dimensions and evaluates heat conduction for each dimension in succession. Terms on the left-hand side of Eq. (7.26) that are not in the orientation being considered are treated as explicit terms. With this technique, a matrix with elements along the diagonal, super-diagonal and sub-diagonal is generated enabling a tridiagonal matrix solver to be used. In addition to much faster solution times compared to solvers used for “full” matrices, this technique has the advantage of not having to store the off-diagonal terms which are primarily zeros and, for a three-dimensional solution domain, this significantly reduces the computational memory requirements. Another advantage of the ADI method is that the accuracy of the solution improves to second order with respect to time.\(^79\)

For a rectangular prism that is discretized for a finite-difference scheme, twenty-seven nodal volume energy balances exist: six faces, twelve edges, eight corners and the interior. The ADI technique used for the billets requires these equations to be derived in each orientation producing a total of eighty-one energy balances. Where applicable, these energy balances incorporate the following boundary conditions:
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\[ y = Y, \ k_{sl} \left( \frac{\partial T}{\partial y} \right) = q_{i, net} \text{, (evaluated from the chamber module)} \]  \hspace{1cm} (7.27)

\[ x = 0, \ k_{sl} \left( \frac{\partial T}{\partial x} \right) = q_{back} \text{ (evaluated from the gap module)} \]  \hspace{1cm} (7.28)

\[ x = X, \ k_{sl} \left( \frac{\partial T}{\partial x} \right) = q_{front} \text{ (evaluated from the gap module)} \]  \hspace{1cm} (7.29)

\[ y = 0, \ k_{sl} \left( \frac{\partial T}{\partial y} \right) = q_{bottom} \text{ (evaluated from the gap module)} \]  \hspace{1cm} (7.30)

\[ z = 0, \ k_{sl} \left( \frac{\partial T}{\partial y} \right) = 0 \text{, (for a furnace with centreline symmetry)} \]  \hspace{1cm} (7.31)

\[ z = Z, \ k_{sl} \left( \frac{\partial T}{\partial z} \right) = q_{end} = \sigma e_{eff}(T_{wall}^4 - T_{end, sl}^4) \]  \hspace{1cm} (7.32)

It is assumed that the billets are charged at a homogeneous temperature.

The design of the stationary beams, which are shown in Figure 7.10, are different than most furnaces in that the thickness of the refractory casing is relatively large. The role of the
Figure 7.10: The location of the stationary beams relative to the billets.

Water-cooling is to maintain refractory strength, however, the beams are known to experience some wear on the corners furthest from the water cooling. For bottom surface nodes that are in contact with the stationary beams, the value for $q_{\text{bottom}}$ in Eq. (7.30) is evaluated from

$$q_{\text{bottom}} = \left( \frac{T - T_{\text{water}}}{R_{sb}} \right)$$

(7.33)

where the stationary beam thermal resistance, $R_{sb}$, is represented by,

$$R_{sb} = \frac{1}{h_{\text{contact}}} + \frac{dx_{sb}}{k_{sb}} + \frac{1}{h_{\text{water}}}$$

(7.34)

The contact heat transfer coefficient was taken to be 200 W/m$^2$-K,$^5$ the thickness and thermal conductivity of the high wear, stationary beam refractory as 0.13 m and 5 W/m-K, respectively,
and the forced convection heat transfer coefficient to the water was estimated to be at least 500 W/m\(^2\)-K. Given these values, the thermal resistance is dominated by the refractory and model calculations indicate that the heat extracted by the water-cooling is small. The formation of skid-marks is primarily a result of the radiative shielding provided by the stationary beams. This conclusion is supported by the billet pyrometer results at Company A where increasing temperature differentials across the billet face were strongly related to decreasing average discharge temperature. Time is required to conduct heat from regions of the billet that are exposed to radiative heat transfer to those that are shielded by the stationary beams. With decreasing average discharge temperature, the residence time of the billets within the furnace is usually smaller.

Heat transfer to the ends of the billet was simplified by a similar approach used by Li et al.\(^8\) An effective emissivity between the end of the billet and the wall of the furnace is calculated using the cross-string method\(^7\) and the following relationship:

\[
\varepsilon_{\text{eff}} = \left( \frac{1}{\varepsilon_{\text{wall}} A_{\text{wall}} + \frac{1}{A_{\text{wall}} F_{\text{wall}}^{\rightarrow \text{st}}} + \frac{P_{\text{st}}}{\varepsilon_{\text{st}} A_{\text{st}}}} \right)^{-1} \tag{7.35}
\]

The pacing rates and initial charging temperature are included in the data packets contained in FIRING.DAT. This allows for an examination of cold charging, hot charging or even a mixture of both as a function of time. Thermophysical properties for 0.23%C and 0.8%C were obtained from the British Iron and Steel Research Association and phase changes are incorporated in the specific heat data.\(^8\)

In order to test the billet code, simulations were carried out where a specified heat flux was applied to each face in succession. In addition to the expected symmetry, the predicted temperatures were similar to a one-dimensional model that had been validated with an analytical solution.\(^8\) The code was tested in three-dimensions by applying heat fluxes that are representative
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of the charge zone: \( q_{\text{top}} = 175 \text{ kW/m}^2 \), \( q_{\text{bottom}} = 75 \text{ kW/m}^2 \), and \( q = 100 \text{ kW/m}^2 \) on the forward and back faces. Simulations representing one hour of heating time were carried out varying the nodal density and the time step. Because there are forty to sixty billets in the furnace that have to be modelled, excessive billet discretization would produce unacceptably long execution times. However, a sufficient number of nodes is required for comparison to the thermocouple measurements obtained during the plant trials. A billet (0.15 m x 0.15 m x 2.22 m) was discretized with three nodal densities: \( 7 \times 7 \times 41 \), \( 9 \times 9 \times 41 \) and \( 11 \times 11 \times 41 \). The higher two densities produced identical centreline and surface temperatures, whereas the surface temperatures of the lowest nodal density were 0.2% smaller after one hour. Simulations using the \( 9 \times 9 \times 41 \) nodal density (base case) and time steps of 15 s, 30 s and 60 s gave identical temperatures and this is expected since the ADI scheme is second order accurate with respect to time. The time step that is employed in the model has therefore been set to the walking beam stroke rate. The model developed at Inland Steel uses a time step of 150 seconds.\(^{24}\)

7.4.7 Heat Transfer in the Hearth

Heat transfer to the top of the hearth is not expected to be large because it is partially shielded from the furnace chamber by the billets. Further, because of the thermal resistance of the refractory, the majority of the thermal energy that enters the gaps is absorbed by the relatively colder steel. Conduction in the hearth is primarily through the thickness of the refractory, although some heat may conduct from exposed regions (boundary 7 in Figure 7.8) to regions underneath the billets (boundaries 6 and 8). Heat transfer is solved in two-dimensions in the same plane as the gap module, which is parallel to the furnace axis and transverse to the billet axis, and it is assumed that heat flow in the remaining orientation can be neglected. The governing equation is then

\[
\frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_h \frac{\partial T}{\partial z} \right) = \rho H C_p h \frac{\partial T}{\partial t} \tag{7.36}
\]

The through thickness is indicated by the direction \( y \) whereas \( z \) represents the orientation parallel
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to the furnace axis. Heat transfer within this domain is evaluated using a two-dimensional, ADI, finite-difference scheme with the following boundary conditions:

\[ y=Y, \; k_h \left( \frac{\partial T}{\partial y} \right) = q_{top} \text{ (evaluated from the gap module)} \] (7.37)

\[ y=0, \; k_h \left( \frac{\partial T}{\partial y} \right) = -h_{amb} (T - T_{amb}) \] (7.38)

\[ z=0, \; z=Z, \; k_h \left( \frac{\partial T}{\partial x} \right) = -h_{amb} (T - T_{amb}) \] (7.39)

For Company A’s furnace, the hearth is 17.4 m in length and 0.3 m thick and is discretized by 601x7 nodes. Thermophysical data that was available for the castable refractory (Narco Plicast LWI 24R) included the density, 1362 kg/m³, and temperature dependent thermal conductivities (ranging from 0.33-0.5 W/m-K). A polynomial expression for the specific heat of typical furnace refractory materials was obtained from [65].

7.4.8 Heat Transfer through the Furnace Roof and Walls

For each of the refractory surface zones in the chamber module, one-dimensional heat transfer is calculated using a Crank-Nicholson, finite-difference scheme. This scheme averages the conduction component of the governing heat transfer equation over the time step, \( \Delta t \), and is expressed as

\[ 0.5 \left( \frac{\partial}{\partial x} \left( k_r \frac{\partial T}{\partial x} \right) \right)_t + 0.5 \left( \frac{\partial}{\partial x} \left( k_r \frac{\partial T}{\partial x} \right) \right)_{t+\Delta t} = \rho C_p, \frac{\partial T}{\partial t} \] (7.40)

As with the ADI technique, the Crank-Nicholson scheme is also second-order accurate with respect to time thus providing improved accuracy. The boundary condition at the interior face is
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\[ k_r \left( \frac{\partial T}{\partial x} \right) = q_{i, \text{net}} \text{ (obtained from the chamber module)} \]  

(7.41)

and at the exterior boundary

\[ k_r \left( \frac{\partial T}{\partial x} \right) = -h_{\text{amb}} (T - T_{\text{amb}}) \]  

(7.42)

The refractory thickness of 0.3 m is represented by seven nodes. As was the case for the hearth, thermophysical data were obtained from both Company A and Rhine and Tucker.\(^6^5\)

7.4.9 Scaling and Decarburization Modules

Because scale formation represents a loss of material and decarburization affects the surface properties of the steel, modules to account for these phenomena have been included in several furnace models.\(^{41,44,53,82-84}\) The majority of scaling models employ a parabolic rate law,

\[ \frac{dx^2}{dt} = A_s e^{-Q/RT} \]  

(7.43)

where \( x \) is the thickness of the scale layer, \( A_s \), the rate constant, and \( Q \), the activation energy, are determined experimentally. It is assumed that the scale layer is primarily FeO and remains attached to the steel. The model used by Fontana incorporates the partial pressures of carbon dioxide and oxygen in the furnace gases as follows

\[ \frac{dx^2}{dt} = 2 \left[ 1.5 \times 10^4 (0.36 + 0.4p_{CO_2} + \min(1, 100p_{O_2})) \right] e^{-\frac{20380}{T}} \]  

(7.44)

As indicated earlier, the atmospheres of both furnaces in this study have an oxygen content of at least 1.0% which would simplify this equation. In this study, the data from Abuluwefa et al\(^8^4\) is
used where \( A_s = 0.039 \text{ cm}^2/\text{s} \) and \( Q/R = -16600 \text{ K} \).

Decarburization models are generally based on the solution of Fick's law which can be described in one-dimension as:

\[
\rho \frac{\partial Y_c}{\partial t} = \frac{\partial}{\partial x} \left( \rho D \frac{\partial Y_c}{\partial x} \right)
\]

(7.45)

The steel surface temperature in a reheating furnace increases rapidly such that the surface is in the austenite phase thus requiring a single diffusion coefficient. It is further assumed that the carbon concentration at the scale/steel interface is zero since the scale layer is considered porous allowing oxygen to reach this interface. Decarburization depth is reported as the location where the carbon concentration falls below a specified percentage (i.e., 90%) of the original concentration. The data from Abuluwefa et al.\(^{84}\) is used in this study where \( D = 0.15 \exp (-16310/T) \text{ cm}^2/\text{s} \).

The scale and decarburization layers are approximately one millimeter in thickness and discretizing the billets to this extent would not be practical. The billet temperatures on the top face are therefore used as the characteristic temperatures since this face will exhibit the most severe scaling and decarburization. With this characteristic temperature, scaling and decarburization are modelled assuming a semi-infinite solid having a decarburization depth of one centimeter, i.e., the carbon content at this depth does not change.

### 7.4.10 Charge Movement Through the Furnace - The Tracking Module

Although not numerically complicated, the tracking module regulates billet charging, advancement, and discharging from the furnace. Using a control variable that is read from FIRING.DAT, the model simulates one of five operating modes: preheating, charging, steady-state, delay and recovery. Billet movement occurs during the charging, steady-state and recovery stages. Two modes of billet advancement are possible: single stroke mode where billets are charged on every walking beam cycle (i.e., 0.15 m billets on a 0.27 m stroke) or on alternating
cycles (i.e. 0.20 m billets on every second stroke of 0.20 m). Typical stroke intervals for both cases at Company A are 51 and 44 seconds, respectively and the model uses this interval as the time step.

For each billet charged into the furnace, a file is created for the recording of residence time, distance into the furnace, key temperatures, and scaling and decarburization thicknesses. Billet temperatures are stored in a single array with each billet identified by its position relative to the soak end. When a billet is discharged, its output file is closed and the global billet temperature array is updated accordingly. With this scheme, the size of the array corresponds to the number of billets in the furnace as opposed to the total number of billets charged, which is about four hundred billets in a typical simulation.
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The mathematical model of a billet reheating furnace was used to fulfill the following objectives:

(i) to validate the model using industrial data,

(ii) to determine process parameters including billet heating profiles and furnace efficiencies,

(iii) to examine current delay strategies and investigate alternatives, and

(iv) to explore other capabilities of the model including modifications to the current steady-state firing strategy, preheated combustion air and hot charging.

The verification of the model and subsequent simulations has been limited to 0.15 m billets at Company A owing to the availability of gas flow data. Since the beginning of this study, Company A had been upgrading their furnace focusing primarily on the zone controls and the measurement of natural gas and combustion air flows. In addition to the plant trial results, this has lead to the fine-tuning of the air/fuel ratios to fire more leanly in the soak zone and the lowering of the zone set-points resulting in significant fuel savings.

Furnace modifications planned at Company B include the upgrading of the recuperator so that it can operate at higher temperatures and the installation of several preheat burners near the charge entrance. With these changes, furnace performance and billet heating will be significantly different than was observed during the plant trial campaigns. The gas flow data in each zone is logged on the hour and is not of sufficient detail to be utilized by the model where, for example, the gas flows in each zone during delays cannot be determined. The volume of leakage air entering the charge entrance, which is expected to be large, also cannot be measured. It is for these reasons that the current modelling analysis has focussed on Company A’s furnace.
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8.1 Model Verification

Verification is an important stage in the development of a mathematical model and, in this study, the verification procedure was directed at:

(i) ensuring the model is capable of simulating steady-state furnace operation,
(ii) extending the simulation to transient operation, and
(iii) assessing the validity of assumptions employed in the model, i.e. the plug flow approximation used for the furnace gases.

It may be recalled that mill throughput at Company A was limited by the reheating furnace. This results in the charge and heat zones being heavily fired with the billet discharge temperatures controlled by the soak zone firing rate and the pacing rate. The measured steady-state gas flows in the soak zone are about 40% of the charge and heat zones (Table 8.2).

Using these data, the predicted and measured steady-state billet temperatures are shown in Figure 8.1 and are in good agreement. Because extensive billet discretization would produce unacceptably long execution times, the predicted temperatures represent the closest finite-difference node relative to the thermocouple position. In addition, furnace gases exiting through the charge entrance provide a slight pre-heating of the billets while on the charge skid and this has been neglected. The calculated residence time of 56 min. is similar to that recorded during the billet test when the short stoppage at the 50th minute is taken into account. The good agreement between the measured and predicted heating profiles supports the assumption that the extent of back-mixing of the furnace gases is relatively small. The predicted discharge temperature of 1236°C at the core of the billet also agrees well with the measurements, again taking the short stoppage near the end of the test into account. The average temperature recorded by the billet pyrometer was 1130°C and the model provides further indication that the actual dropout temperatures are hotter.
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>billet width (m)</td>
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</tr>
<tr>
<td>billet length (m)</td>
<td>4.78</td>
</tr>
<tr>
<td>stroke distance (m)</td>
<td>0.27</td>
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<tr>
<td>stroke interval (s)</td>
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</tr>
<tr>
<td>production rate (tonnes/h)</td>
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</tr>
<tr>
<td>gas flows ($10^3$ m$^3$/h)</td>
<td>gas/air</td>
</tr>
<tr>
<td>Charge zone</td>
<td>1.39/13.99</td>
</tr>
<tr>
<td>Heat zone</td>
<td>1.41/14.44</td>
</tr>
<tr>
<td>Soak zone</td>
<td>0.57/6.34</td>
</tr>
</tbody>
</table>

Table 8.1: Billet and gas flow data used for the steady-state verification of the mathematical model.

![Graph of billet temperatures](image)

Figure 8.1: Measured and predicted billet temperatures for steady-state furnace operation (symbols refer to measurements, lines refer to model predictions).
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When a billet is discharged from the furnace, it passes through a descaler before the surface temperatures are measured with an optical pyrometer. These temperatures would be expected to be colder than the interior of the billet because of the quenching caused by the descaler's high pressure water jets. The water flow rate is not measured, however, it is assumed that the heat extracted from the billet surface can be characterized by a quench heat transfer coefficient. A billet, initially at 1200°C, was subjected to a range of quenching heat transfer coefficients for 0.2 s where it is assumed that this interval represents the length of time a point on the surface of the billet is cooled by the descaler water jets. The quench heat transfer coefficients were varied from 0 to 10 kW/m²-K, which is in the range of forced convection, and the results are shown in Figure 8.2. From radiation alone, the surface temperature of the billet decreases 28°C after 15 s. A quench heat transfer coefficient of 5 kW/m²-K produced a sudden drop of 33°C with the total decrease in surface temperature being 51°C. For a heat transfer coefficient of 10 kW/m²-K, the predicted decrease in surface temperature during the quench is 64°C. In this case, the surface temperature rebounds about 15°C giving a net decrease in the surface temperature of 88°C. From these results, it can be concluded that the differences between the pyrometer readings and both the measured and predicted billet temperatures are due to the descaler.

The predicted steady-state gas temperatures are shown in Figure 8.3. For each position along the length of the furnace, two gas temperatures are reported by the model representing the gas zone near the centre of the furnace, which is hotter, and the gas zone next to the wall. There is reasonable agreement between the measured and predicted gas temperatures in the charge and heat zones, particularly if allowance is made for the fact that the sampling ports correspond to the gas zones near the wall. The soak zone temperature, which is indicated by (a) in the figure, is about 150°C colder than the predicted temperature. It is not apparent why there is such a dramatic decrease in this particular temperature relative to the charge and heat zones. However, the soak zone temperature recorded during the next steady-state billet test (A2-2), which is indicated by (b) in the figure, is closer to both the charge and heat zone measured temperatures as well as the predicted temperatures. In this figure, the predicted temperature of the gas zone near the wall and
Figure 8.2: Influence of a quench heat transfer coefficient on a billet subjected to water spray for 0.2 s.

12.6 m into the furnace drops to 1391°C due to the burner in this zone being closed during this trial.

The firing data employed in the delay simulation, which is given in Table 8.2 and shown in Figure 8.4, were obtained from the third billet test of the second plant trial campaign (A2-3). Although the mathematical model can be used to examine firing strategies during furnace charging, these data were not recorded and the gas flows used for the charging stage were selected to rapidly bring billet heating to steady-state.

The predicted and measured temperatures for the test billet are presented in Figure 8.5 and again show good agreement. In this simulation, it was necessary for the modelled test billet to be at the same position in the furnace at the start of the delay. This is defined as “A” in the figure and represents a residence time of 12 min. From the furnace log, the length of the delay was 65 min. and this defines the return to full firing, “B”. The results from this simulation indicate that the
Figure 8.3: Measured and predicted gas temperatures for steady-state furnace operation ((a) test A2-1, (b) test A2-2).

<table>
<thead>
<tr>
<th>Gas flows ($10^3 \text{ m}^3/\text{h}$):</th>
<th>gas/air</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Charge zone</td>
</tr>
<tr>
<td>before the delay:</td>
<td>1.39/13.99</td>
</tr>
<tr>
<td>during the delay:</td>
<td>0.11/1.84</td>
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<tr>
<td>first 40 min. following the delay:</td>
<td>1.39/13.99</td>
</tr>
<tr>
<td>remainder of the simulation:</td>
<td>1.39/13.99</td>
</tr>
</tbody>
</table>

Table 8.2: Gas flow data used for the verification of the mathematical model during a furnace delay.

Billets continue to increase in temperature during the delay even though the firing was significantly reduced. The minimum levels are necessary to ensure the burners remain lit and the results indicate that the heat generated from combustion during the delay is sufficient to continue heating the billets.

From the figure, it is apparent that the model over-predicts discharge temperatures by
Figure 8.4: Gas flow data used for the verification of the transient component of the mathematical model.
Figure 8.5: Measured and predicted temperatures for a test billet with a 65 min. delay in the charge zone (symbols refer to measurements, lines refer to model predictions).

about 30°C. Two readings of natural gas and combustion air flows were recorded following the delay and these are included in Figure 8.4. In practice, the PID controller will gradually increase the firing following the delay, however, during the second plant trial campaign this data was not being logged. Better predictions for the billet discharge temperatures would be expected with more representative gas flow data.

8.1.1 General Thermal Behavior of the Reheating Furnace

For the steady-state heating of 0.15 m billets, the energy from combustion is 36.4 MW and the energy removed in the flue gases is 24.9 MW, or 68% of the combustion energy. The heat transferred to the billets is 11.2 MW giving a thermal efficiency of 31% and, assuming continuous operation, a fuel consumption of 2.17 GJ per tonne of steel. From January, 1993, to June, 1994, the fuel consumption logged at Company A averaged 2.48 GJ/tonne. There are two reasons why this value is greater than the predicted value.
(i) Over this period, the furnace was on warm idle 14.5% of the time.

(ii) The processing of 0.20 m billets requires higher fuel consumption per tonne of steel and therefore raises the average.

The remainder of the energy, 0.3 MW (0.8%), is lost through the furnace refractory.

Calculated gas, roof and wall surface temperatures in each of the furnace zones are plotted as a function of time in Figure 8.6. During steady-state operation (just prior to a simulation time of 200 min.), the roof temperatures are 1190°C, 1283°C, and 1340°C, for the charge, heat and soak zones, respectively. In the simulation, the firing strategy employed during charging rapidly brought the furnace to steady-state operation and this resulted in high roof and wall temperatures in the heat zone exceeding 1600°C in both cases (the recommended maximum operating temperature for this refractory is 1650°C). Although not considered an objective of this study, the furnace model can also be used to develop firing strategies during charging.

During the delay, the gas temperatures rapidly decrease in response to the firing being reduced. With time however, the gas temperatures slowly begin to rise since the billets in the furnace continue to increase in temperature. After the delay when the firing is increased, the predicted gas and refractory temperatures in the charge and heat zones temporarily overshoot the steady-state values, and this is again attributed to the billets having increased in temperature during the delay. The temperatures in the soak zone decrease since the firing in this zone was actually reduced after the delay.

The billet temperature and heat flux profiles as a function of furnace position during steady-state operation are shown in Figure 8.7. The average temperature and standard deviation are evaluated over the entire billet, the minimum temperature is located on the bottom face of the billet that is in contact with the stationary beam, and the top face temperature is an averaged value. Compared to Figure 8.3, the variation in temperature appears greater because of the top face temperature, with a differential between the top face and average temperatures of about
Figure 8.6: Gas, roof and wall temperatures for each control zone during the transient simulation.
Figure 8.7: Steady-state temperature and heat flux profiles for Company A's reheating furnace while heating 0.15 m billets.

300°C in the charge zone. With a soaking stage not being practiced at the company, the heat flux profile can be seen to be somewhat linear varying from 182 kW/m² in the charge zone to 56 kW/m² in the soak zone.

Compared to the steady-state results, the amount of energy transferred to the billets 55 min. into the 65 min. delay is much lower with a heat flux of 32 kW/m² in the charge zone and 9 kW/m² in the soak zone (Figure 8.8). The positive heat flux profile indicates that the billets continue to receive thermal energy during the delay as a result of the 5.2 MW of energy generated from combustion. The predicted billet temperatures near the charge entrance exceed 500°C where they would be closer to ambient temperature during steady-state. The temperature profiles also indicate the billets become more homogenized in temperature as a result of the increasing residence time in the furnace.

In Figure 8.9, the temperature and flux profiles 15.7 min. after the delay denote a sudden
change 4.8 m into the furnace where the predicted billet temperatures increase approximately 200°C and the heat flux decreases by about 75 kW/m². This is an important observation as it represents the transition from billets that were in the furnace during the delay to newly charged billets. When a control zone contains this transition, the firing is set to a level that brings the new billets to rolling temperatures while minimizing the overheating of the billets that were in the furnace during the delay. One of the objectives of a post-delay firing strategy is to minimize this disparity as the transition point progresses through the furnace. Using the post-delay firing strategy recorded during the plant trial, the predicted temperature differential is reduced to 100°C at the mid-point of the heat zone (Figure 8.10).

8.1.2 Billet Data

During a simulation, the model generates thermal history files for each billet that includes position, residence time, average, maximum, minimum, standard deviation and surface temperatures, as well as scale and decarburization thicknesses. Figure 8.11 shows the tracking of
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the steady-state billet through the furnace and the corresponding increase in enthalpy. The jog in the distance profile in the seventeenth minute reflects a 65 s delay that was recorded by the furnace logs and was also included in the steady-state verification. The billet temperature profiles plotted against residence time are shown in Figure 8.12 and are similar to those presented in Figure 8.7. The calculated steady-state scale thickness of 0.3 mm represents a material loss of 0.6% (Figure 8.13). In comparison, Yuen reports a final scale thickness of 1.5 mm for a slab that is discharged at a temperature of 1225°C from a furnace that is 33 m in length. This length is double the length of Company A's furnace and the amount of time the steel is at higher temperatures is greater. The reported scale thickness 17 m into the slab furnace, where the slab surface temperature is about 1050°C, is 0.2 mm and although it is difficult to precisely compare the two furnaces, the predicted scale thicknesses appear reasonable.

Similar plots were generated for the billet that was used in the transient verification. Figure 8.14 indicates the billet was 2.4 m into the furnace when the delay started and the total

Figure 8.9: Temperature and heat flux profiles 15.7 min. following the delay.
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Figure 8.10: Temperature and heat flux profiles 32.9 min. after the delay.

Figure 8.11: Distance and enthalpy profiles for a steady-state billet.
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Figure 8.12: Temperature profiles for a steady-state billet plotted against residence time.

Figure 8.13: Scale and decarburization thicknesses for a steady-state billet plotted against residence time.
enthalpy increased during the delay. Because the interior temperatures of the billet increased, the driving force for heat transfer from the surface of the billet to the interior was reduced. When the firing was increased after the delay, the top face temperatures increased at a faster rate than the remainder of the billet, as shown in Figure 8.15. This is also reflected in the standard deviation profile with a gradual decrease occurring during the delay followed by a rapid increase when the firing was turned back up. The predicted final scale thickness was slightly higher at 0.4 mm (Figure 8.16) but the billet was not far enough into the furnace during the delay to become sufficiently hot and influence scale formation.

When these results are plotted against furnace position, the effect of the delay becomes more apparent. From the billet temperature profiles shown in Figure 8.17, the billet average temperature increases approximately 400°C during the delay. The predicted scale and decarburization thicknesses shown in Figure 8.18 suggest that the delay did not significantly affect the surface quality of the billet. Scale formation is a function of time and temperature and because the billet was in the colder, charge zone during the delay, the driving force to generate scale was not large. The slight increase in final scale thickness compared to the steady-state billet can therefore be attributed to this billet passing through a hotter furnace following the delay.

It would be expected that a billet further into the furnace during the delay would experience heavier scaling and decarburization. Figure 8.19 shows that the enthalpy of a billet that was in the soak zone during the delay continued to increase but at a lower rate than what was observed in the charge zone billet. The billet temperatures shown in Figure 8.20 indicate the average temperature at discharge was approximately 100°C hotter than during steady-state operation. The predicted final scale thickness was 0.6 mm which is double the steady-state value and represents a material loss of 0.8% (Figure 8.21). When plotted against distance into the furnace, Figure 8.22 shows that the average temperature increased by approximately 175°C during the delay while Figure 8.23 indicates the scale thickness increased from 0.25 mm to 0.6 mm.
Figure 8.14: Distance and enthalpy profiles for a billet residing in the charge zone during the delay.

Figure 8.15: Temperature profiles plotted against time for a billet residing in the charge zone during the delay.
Figure 8.16: Scale and decarburization thickness plotted against time for a billet residing in the charge zone during the delay.

Figure 8.17: Temperature profiles plotted as a function of distance travelled for a billet residing in the charge zone during a delay.
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Figure 8.18: Scale and decarburization thickness plotted against distance travelled for a billet residing in the charge zone during the delay.

Figure 8.19: Distance and enthalpy profiles for a billet residing in the soak zone during the delay.
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Figure 8.20: Temperature profiles plotted against time for a billet residing in the soak zone during a delay.

Figure 8.21: Scale and decarburization thickness plotted against time for a billet residing in the soak zone during the delay.
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Figure 8.22: Temperature profiles plotted against distance travelled for a billet residing in the soak zone during the delay.

Figure 8.23: Scale and decarburization thickness plotted against distance travelled for a billet residing in the soak zone during the delay.
8.2 Application of the Furnace Model

8.2.1 Adjustment to the Air/Fuel Ratios

During steady-state furnace operation at Company A, the excess combustion air was determined to be approximately 2.2%, 4.2% and 12.8% in the charge, heat and soak zones, respectively. The relatively higher levels of excess air in the soak zone reduces the thermal efficiency in this zone, introduces a heat sink (nitrogen) that travels the length of the furnace, and introduces high oxygen levels in a zone where the steel is the hottest and more prone to scaling. It was recommended that the air/fuel ratios be adjusted to fire the soak and heat zones more leanly, while firing the charge zone at about 10% excess air to ensure the fuel is fully combusted prior to leaving the furnace.

A simulation was carried out where the excess air was changed to 10%, 3% and 3% in the charge, heat and soak zones, respectively. In order to reduce model execution times, furnace conditions 200 min. into the steady-state simulation were read from a file. The modified firing strategy was implemented at a simulation time of 220 min. The same amount of natural gas was used in the charge and heat zones, but was reduced to 429 m$^3$/h from 571 m$^3$/h in the soak zone. This decrease was necessary to produce billet average discharge temperatures that were similar to those obtained before the modification.

The average dropout temperatures before and after the change were 1232°C and 1237°C, respectively (Figure 8.24). Even with a 4.4% reduction in total fuel consumption, the modified firing strategy did not lead to significant changes in the average, minimum and top face temperatures. This observation is also valid for the billets that were in the furnace during the change. The benefits of the modified firing strategy have already been realized by the company with the set-points in the soak zone being lowered and a reduction in scale accumulation on the floor of the furnace.

8.2.2 Examination of the Present Delay Strategy at Company A

As indicated in the plant trial data, the firing in each of the control zones is turned down
during the delay. The primary, post-delay firing strategy employed at Company A for a delay in excess of 30 min. is given in Table 8.3. The soak zone set-point temperature of 1220°C applied after the delay is 100°C lower than the steady-state value and acknowledges the billets have continued to increase in temperature during the delay. More importantly, the shutting off of the soak zone controller from the 33rd billet to the 62nd billet is an attempt to use this zone to control the discharge temperatures of the billets that were in the charge zone during the delay.

Since the natural gas and combustion air flows were not being logged during the second plant trial campaign, there is some uncertainty with respect to how quickly a zone returns to steady-state firing immediately after a delay. The zone temperatures recorded during the trials indicated values well below the set-points during the delay and it has therefore been assumed that the firing in each zone after the delay is rapidly returned to steady-state levels (Figure 8.25). With the above post-delay firing strategy, the predicted billet discharge temperatures shown in Figure 8.26 were approximately 40-75°C hotter than the steady-state levels for a period of about
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<table>
<thead>
<tr>
<th>At the end of the delay</th>
<th>soak zone in automatic, bring soak zone temperature up to 1220°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge 1st billet</td>
<td>check temperature to ensure it can be rolled</td>
</tr>
<tr>
<td>2nd to 10th billet</td>
<td>shut off soak zone and set heat and charge zone to automatic</td>
</tr>
<tr>
<td>11th to 32nd billet</td>
<td>all zones set to automatic</td>
</tr>
<tr>
<td>33rd to 62nd billet</td>
<td>shut off the soak zone</td>
</tr>
<tr>
<td>63rd billet and forward</td>
<td>all zones set to automatic</td>
</tr>
</tbody>
</table>

Table 8.3: Post-delay firing strategy employed at Company A for delays in excess of 30 min.

60 min. This represents the time required to process the billets that were in the furnace during the delay and once these billets are discharged from the furnace, it can be seen that the average billet discharge temperatures rapidly returned to steady-state levels. During steady-state operation, billets reside in the soak zone for approximately 13 min. and with such a short period, the influence of changes to the soak zone firing rates on the discharge temperatures is limited.

8.2.3 Improved Delay Strategies

Given that the current delay strategy is based upon adjustments to the soak zone firing rates, strategies that modify the firing rates in the other control zones can also be examined. For these simulations, the primary objective is to minimize the overheating of the discharged billets relative to the steady-state temperatures while avoiding the underheating of newly charged billets. Except where otherwise noted, the firing rates are the same as those used for the simulation of the current post-delay strategy.

(i) delay until a return to full firing in all of the zones

The simplest strategy to implement is the return of all of the zones to full firing after a specified period following the delay. Figure 8.27 shows the billet average discharge temperatures following a 30 min. delay with the firing rates having been increased 0 min., 10 min. and 20 min. after the delay. The 0 min. interval resulted in the average discharge temperatures remaining approximately 100°C above the steady-state value for about 60 min. following the delay. The billet average temperatures were actually hotter than those predicted with the current delay.
Figure 8.25: Gas flow data used for the simulation of Company A's current delay strategy.
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Figure 8.26: Billet discharge temperatures following a 30 min. delay: current delay strategy.

Figure 8.27: Billet discharge temperature following a 30 min. delay: return to full firing 0, 10 and 20 min. from the end of the delay.
strategy (see Figure 8.26). The 20 min. interval is greater than the time required to empty the soak zone of its billets. It can be seen from the figure that the average discharge temperature rapidly fell to below 1100°C which is likely too cold for subsequent rolling operations. The intermediate interval of 10 min. produced a slower decrease in billet average dropout temperature with the minimum occurring 60 min. after the delay at 1197°C.

(ii) sequential return to full firing in each of the zones

A more complicated strategy involves the sequential, or staggered, return to full firing in each of the zones (Figure 8.28). This type of firing pattern was observed when the furnace was being charged or emptied. The objective of this strategy is to give the heat and soak zones more time to cool following the delay while still heating the colder billets entering the charge zone. Two simulations were carried out where the interval for each zone being returned to full firing was 10 min. and 20 min. The 10 min. interval, for example, leads to full firing in the charge zone at 10 min., the heat zone at 20 min., and the soak zone at 30 min. after the delay.

For both simulations, the billet average discharge temperatures reach steady-state levels after about 22 min. (Figure 8.29). The first minimum for the 10 min. interval was 1213°C occurring at the 279 min. mark while for the 20 min. interval it was 1175°C at 289 min. This minimum represents the control of discharge temperatures for billets that were in the heat zone during the delay. Two other profiles are included in the figure: 0 min. and 10 min. return to full firing in all of the zones and it is evident that the sequential firing strategies better control the discharge temperatures of the heat zone billets. In practice, the size of the stagger would be proportional to both the increase in billet temperature during the delay, and thus the delay length, and the pacing rate, which is an indicator of how quickly the overheated billets can be removed from the furnace.

The subsequent increases in the temperature profiles near 290 min. represent the transition point between billets that were in the charge zone during the delay and newly charged billets. An objective of a post-delay firing strategy is to prevent the overheating of the billets that were in the
Chapter 8: Results and Discussion

Figure 8.28: Schematic diagram of the sequential firing strategy.

Figure 8.29: Billet discharge temperature following a 30 min. delay: sequential return to full firing at 10 and 20 min. intervals compared to the resumption of full firing in all zones at 0 and 10 min. from the end of the delay.
charge zone during the delay while adequately heating the newly charged billets. This trade-off produces the second minimum in the temperature profiles where the newly charged billets are discharged slightly colder than the steady-state billets. These minimums were 1209°C and 1183°C for the 10 min. and 20 min. sequential return to full firing, respectively. Alternatively, a spacing (i.e. ~10 billet widths) could be inserted ahead of the newly charged billets; however, the model is not configured to simulate a large gap in the charge.

The ultimate goal of a post-delay firing strategy is to minimize the difference between discharged billet temperatures and the desired heating requirements. The development of heating criteria for each type of product is therefore an important stage in the development of delay strategies. This would lead to upper and lower limits being defined for the billet average discharge temperatures (Figure 8.30). The upper limit would be related to surface melting, oxidation or heating efficiencies. The lower limit is primarily based on billet rollability, such as skidmark severity. Using average discharge temperatures after a 30 min. delay, the sequential return to full firing with a 10 min. interval produces temperatures closest to the steady-state values. This delay strategy is an improvement over the current strategy practiced at the company since it includes the firing rates in the charge and heat zones. The development of delay strategies must also account for the transition between billets in the charge zone during the delay and newly charged billets. In the plant trial results of Chapter 5, "undulations" in billet temperatures following furnace stoppages were identified, an example of which is shown in Figure 8.31. It is believed that this phenomena is due to the furnace controls attempting to respond to this transition.

### 8.2.4 Billet Pacing

Billet pacing during steady-state operation is limited by adequate heating or other constraints in the mill including full cooling beds. For certain types of delays, such as those caused by cobbles, the cooling beds become emptied. This permits faster pacing rates to be used after these delays in order to remove the overheated billets in the soak zone. Once the cooling beds are filled, the pacing rate is returned to steady-state levels. Although not part of the documented delay strategies, some of the operators followed this practice while closely
To examine the effect of changing the pacing rate, two simulations were carried out with walking beam stroke intervals of 46.44 s (-10% of the baseline) and 56.76 s (+10%). These changes were again initiated at a simulation time of 220 min. The average and minimum temperatures of the discharged billets are shown in Figures 8.32 and 8.33. For the baseline case with a stroke interval of 51.6 s, the average temperature was 1231°C and the minimum temperature was 1138°C. With a stroke interval of 56.76 s these increased to 1288°C and 1201°C, respectively, after 60 min. They decreased to 1161°C and 1056°C with a stroke interval of 46.44 s. The stroke interval produced larger changes for the minimum temperatures and this agrees with the earlier observation that billet minimum temperatures are influenced by soaking times.
Figure 8.31: Billet average and maximum discharge temperatures at Company A on June 7, 1994, showing “undulations” following a delay.

8.2.5 Hot Charging

Hot charging can substantially reduce specific energy consumption. Although not normally practiced at the company, a shortage of billets during the second plant trial campaign resulted in billets being charged into the furnace at temperatures above ambient temperature. Under these conditions, the steady-state zone set-point temperatures are no longer applicable and the operator must closely monitor the performance of the furnace as well as billet discharge temperatures. The model was used to explore furnace performance under hot charging conditions by considering two scenarios:

(i) reduction in firing rate, throughput maintained constant

For these simulations, an initial billet temperature of 300°C was used since this was estimated to be the hot charging temperature during the second plant trial. With the furnace operating at steady-state, hot billets were charged at a simulation time of 220 min. To compensate
Figure 8.32:  Effect of the walking beam stroke interval on billet average discharge temperatures.

Figure 8.33:  Effect of stroke interval on billet minimum temperatures at discharge.
for the higher temperatures, the gas flows in each of the zones were reduced to 75% of the steady-state values in a sequential manner: at 220 min. for the charge zone, at 240 min. for the heat zone, and at 260 min. for the soak zone (Table 8.4).

The steady-state billet average discharge temperatures, which are shown in Figure 8.34, before and after hot charging were 1232°C and 1225°C, respectively. The firing strategy used for this simulation enabled a smooth transition from cold to hot charged billets with a small dip in temperature occurring at the 274 min. mark. This dip is attributed to the temperature increase between the cold billets and newly charged hotter billets. The reduced firing for the hot charged billets causes the nearby cold charged billets to be slightly underheated. The standard deviation in the temperatures of the discharged billets decreases from 51.8°C to 43.0°C with hot charging and the difference between the top face and minimum temperatures also decreases going from about 235°C to 200°C. These results suggest that the quality of billet heating has improved with the hot charging.

The thermal efficiency with hot charging slightly increased to 32.3% from 30.8% because of the lower firing rates. The steady-state temperature profiles for a hot charged billet, which are shown in Figure 8.35, indicate that the top face was at higher temperatures for a longer time thus increasing the potential for scale formation.

(ii) increased furnace throughput, firing rate held constant

Higher furnace throughputs can improve the efficiency of a rolling mill in terms of tonnes of finished steel produced per man-hour. With hot charging, this is achieved by increasing the pacing rate while maintaining relatively high firing rates. For a rolling schedule that includes both hot and cold charging, the ability to adjust furnace pacing in response to changes in charging temperature, and thus maintain high production, is important. It is assumed that the pacing rate is gradually increased in relation to the number of hot charged billets that are in the furnace.
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### Table 8.4: Gas flows used in the hot charging simulation.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Original gas flows Gas/Air ($10^3$ m$^3$/h)</th>
<th>Gas flows during hot charging Gas/Air ($10^3$ m$^3$/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>charge</td>
<td>1.39/13.99</td>
<td>1.04/10.49</td>
</tr>
<tr>
<td>heat</td>
<td>1.41/14.44</td>
<td>1.06/10.83</td>
</tr>
<tr>
<td>soak</td>
<td>0.57/6.34</td>
<td>0.43/4.76</td>
</tr>
</tbody>
</table>

Figure 8.36 shows the discharge temperatures for a simulation employing the following discharge intervals: 51.6 s (baseline) up to 220 min., 50.0 s up to 270 min., 47.5 s up to 340 min., and 45.0 s up to 450 min. The average temperature of the discharged billets at the end of the simulation when steady-state is reached was 1234°C and this is close to the discharge temperature of 1232°C during cold charging. At a stroke interval of 45.0 s, the furnace throughput is 69.3 tonnes per hour and represents an increase of 15%. However, the thermal efficiency decreased slightly to 29.4% from 30.8% because the hotter billets in the charge zone absorbed less thermal energy from the exiting gases. The steady-state temperature profiles for the hot charged billets (Figure 8.37) reveal a greater differential between the top face and average temperatures compared to the previous example with hot charging. This difference is due to the faster pacing rates and reduced billet soaking times.

#### 8.2.6 Preheated Air

The mathematical model is also capable of examining the use of preheated combustion air. At Company B, the preheated air temperature was approximately 500°C and this temperature is used in this simulation. This change is applied at the start of the simulation since the model is currently configured for a constant preheated air temperature. The billet discharge temperatures shown in Figure 8.38 were obtained using the gas flows given in Table 8.5 which are 60% of the original steady-state values. The average discharge temperature of the billets at the end of the simulation was 1237°C and the thermal efficiency increased to 38.5%. The predicted gas temperatures are shown in Figure 8.39 with the temperatures mid-length along the furnace exceeding 1650°C. Higher flame temperatures may result in higher NO$_X$ emissions. It is evident in the table that hotter combustion air temperatures lead to higher air flows in order to supply the
Figure 8.34: Predicted billet discharge temperatures from the hot charging simulation with the firing rate in each zone reduced to 75%.

Figure 8.35: Steady-state billet temperature profiles from the hot charging simulation with the firing in each zone reduced to 75%.
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Figure 8.36: Predicted billet discharge temperatures from the hot charging simulation where the discharge interval was reduced.

Figure 8.37: Steady-state billet temperature profiles from the hot-charging simulation where the discharge interval was reduced.

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necessary oxygen for combustion. This would likely require Company A to increase the blower capacity for the combustion air in addition to the installation of a recuperator.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Original gas flows Gas/Air ($10^3$ m$^3$/h)</th>
<th>Gas flows with preheated combustion air Gas/Air ($10^3$ m$^3$/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>charge</td>
<td>1.39/13.99</td>
<td>0.83/22.14</td>
</tr>
<tr>
<td>heat</td>
<td>1.41/14.44</td>
<td>0.85/22.86</td>
</tr>
<tr>
<td>soak</td>
<td>0.57/6.34</td>
<td>0.34/10.04</td>
</tr>
</tbody>
</table>

Table 8.5: Gas flows used in the preheated combustion air simulation.

Figure 8.38: Predicted billet discharge temperatures from the simulation using preheated combustion air at 500°C.
Figure 8.39: Predicted gas temperatures with recuperatively preheated combustion air at 500°C. Lower and upper set of data points represent the outside (near wall) and inside gas volumes, respectively.
Chapter 9: Conclusions

A mathematical model that is capable of simulating the thermal behavior of a billet reheating furnace has been developed and verified against plant trial data obtained on two commercial furnaces. Based on observations from the plant trials and simulations using the mathematical model, the following conclusions can be made:

(i) Billet reheating furnaces seldom operate under steady-state. Furnace control relies on zone thermocouples that use set-points determined from near steady-state conditions and pyrometer measurements from discharged billets. Neither are able to predict billet temperatures while inside of the furnace and future discharge temperatures; especially under non steady-state operation.

(ii) At plants where throughput is furnace limited, heavy firing should be employed in the charge and heat zones to rapidly transfer thermal energy to the billets. However, the firing should be reduced in the soak zone in order to homogenize billet temperatures and limit surface melting, scaling and decarburization. For these furnace, thermal efficiencies are relatively low because of the high firing rates per tonne of steel and recuperators should be employed to recover some of this energy. Higher pacing rates result in severe skidmarks as well as top/bottom and surface/interior temperature gradients.

(iii) For plants where throughput is limited elsewhere, i.e. the roughing stage, firing should be heaviest in the heat zone increasing the residence time of the furnace gases and thus improving the overall thermal efficiency. In these furnaces, long billet residence times allow for the adequate soaking of the skidmarks; however, without proper furnace control, excessive scaling, decarburization and surface melting may occur.

(iv) Good control of the furnace atmosphere leads to the soak and heat zones being fired leanly to improve the thermal efficiency in these zones and minimise scaling. The charge zone is fired at higher levels of excess combustion air to ensure the fuel has been fully combusted prior to leaving the furnace. Additionally, adequate furnace pressures should be maintained to prevent cold, leak-
age air from entering the furnace.

(v) The experimental measurements and modelling results confirm gap heat transfer is an important heating mechanism for walking beam, billet reheating furnaces that have a hearth floor. A trade-off exists where increasing the gap size will increase the rate of billet heating, but at the cost of lower furnace throughputs. A key assumption where convection in the gap could be neglected was supported by the good agreement between measured billet temperatures and model predictions.

(vi) Data from the second plant trial campaign at Company A were used to verify the mathematical model for both steady-state and transient operating conditions. During steady-state operation, this furnace was operating at a thermal efficiency of 31% while the exiting flue gases contained 68% of the combustion energy. The plant data and modelling results indicate that billets continue to increase in temperature during delays even though the burners were significantly turned down. For these furnaces, the development of delay strategies therefore focuses on the recovery of the furnace after a delay.

(vii) A delay strategy that uses the soak zone firing rate to control billet discharge temperatures has limited success since the billet residence times in this zone are short. Alternative delay strategies that utilize the firing rates in the charge and heat zones were examined with the mathematical model. For a 30 min. delay while heating 0.15 m billets, the results indicate that a 10 min. sequential firing interval provided minimal billet overheating while maintaining adequate discharge temperatures of billets charged into the furnace after the delay.

(ix) In addition to developing delay strategies, the model was also used to investigate other aspects of furnace operation including:

(a) The refinement of steady-state air/fuel ratios in each of the zones of Company A's furnace offered a fuel saving of 4.4% over current conditions.
Chapter 9: Conclusions

(b) Even moderate levels of hot charging at 300°C would produce a fuel savings of approximately 25% or an increase in furnace throughput of about 15%.

(c) A potential fuel saving of 40% over current operating conditions could be realized using recuperatively preheated combustion air at a temperature of 500°C.
Chapter 10: Future Work

Following the development and successful verification of a three-dimensional, transient, thermal model of a billet reheating furnace, areas where the model could be further employed include:

(i) Given that the general delay strategy framework involves the sequential return to full firing in each zone, further development would see these strategies being implemented into an expert system. Several scenarios have to be examined since the time at which full firing is re-established will depend on the type of product being heated and the delay length.

(ii) The model provides the opportunity for developing a “reheating quality index”, or RQI, that can be used to assess the effectiveness of different delay strategies. The criteria that would go into this parameter include:

(a) billet discharge temperature,

(b) temperature homogeneity including skidmark severity,

(c) production rate,

(d) extent of scale, decarburization and surface melting,

(e) development of craze cracking due to the presence of Cu at the surface, and

(f) fuel consumption.

As demonstrated in this study, these criteria are often opposing. For example, increasing the production rate usually leads to more severe skidmarks. The weights applied to each of these criteria are therefore both company and product dependent. Due to a 25% increase in natural gas costs,
there is a desire at both companies to reduce fuel consumption which also demonstrates the need to make these weights dynamic. With the increasing competitiveness among steel companies, an RQI would also be useful in ensuring good quality control at the reheating stage.

(iii) Because natural gas and combustion air flows have recently been logged at Company A, a detailed analysis of changes in the gas flows in response to furnace delays should generate new knowledge. This is necessary in order to assess the current heating strategies with the mathematical model.

(iv) The furnace model could also be implemented into a real-time, mill wide control system. Testing on an Intel Pentium-166MHz computer has demonstrated that the model can operate in one third of "real" time. Discharge temperatures predicted by the reheating furnace model, which would include fluctuations resulting from delays, could be used by subsequent roughing and finishing models.
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Appendix A: Logged Furnace Data from the First Plant Trial Campaign at Company A - June 7 to June 10, 1994
Figure A.1: Average and maximum temperatures measured by the billet pyrometer at Company A on June 7, 1994.

Figure A.2: Minimum temperatures measured by the billet pyrometer at Company A on June 7, 1994.
Figure A.3: Measured and set-point temperatures for the charge zone on June 7, 1994.

Figure A.4: Measured and set-point temperatures for the heat zone on June 7, 1994.
Figure A.5: Measured and set-point temperatures for the soak zone on June 7, 1994.

Figure A.6: Billet temperature differentials and standard deviations calculated from the pyrometer readings on June 7, 1994.
Figure A.7: Billet temperature differentials and standard deviations plotted against average discharge temperatures on June 7, 1994.

Figure A.8: Billet temperature differentials and standard deviations plotted against minimum temperatures (east hearth block) on June 7, 1994.
Figure A.9: Average and maximum temperatures measured by the billet pyrometer at Company A on June 8, 1994.

Figure A.10: Minimum temperatures measured by the billet pyrometer at Company A on June 8, 1994.
Figure A.11: Measured and set-point temperatures for the charge zone on June 8, 1994.

Figure A.12: Measured and set-point temperatures for the heat zone on June 8, 1994.
Figure A.13: Measured and set-point temperatures for the soak zone on June 8, 1994.

Figure A.14: Billet temperature differentials and standard deviations calculated from the pyrometer readings on June 8, 1994.
Figure A.15: Billet temperature differentials and standard deviations plotted against average discharge temperatures on June 8, 1994.

Figure A.16: Billet temperature differentials and standard deviations plotted against minimum temperatures (east hearth block) on June 8, 1994.
Figure A.17: Average and maximum temperatures measured by the billet pyrometer at Company A on June 9, 1994.

Figure A.18: Minimum temperatures measured by the billet pyrometer at Company A on June 9, 1994.
Figure A.19: Measured and set-point temperatures for the charge zone on June 9, 1994.

Figure A.20: Measured and set-point temperatures for the heat zone on June 9, 1994.
Figure A.21: Measured and set-point temperatures for the soak zone on June 9, 1994.

Figure A.22: Billet temperature differentials and standard deviations calculated from the pyrometer readings on June 9, 1994.
Figure A.23: Billet temperature differentials and standard deviations plotted against average discharge temperatures on June 9, 1994.

Figure A.24: Billet temperature differentials and standard deviations plotted against minimum temperatures (east hearth block) on June 9, 1994.
Figure A.25: Average and maximum temperatures measured by the billet pyrometer at Company A on June 10, 1994.

Figure A.26: Minimum temperatures measured by the billet pyrometer at Company A on June 10, 1994.
Figure A.27: Measured and set-point temperatures for the charge zone on June 10, 1994.

Figure A.28: Measured and set-point temperatures for the heat zone on June 10, 1994.
Figure A.29: Measured and set-point temperatures for the soak zone on June 10, 1994.

Figure A.30: Billet temperature differentials and standard deviations calculated from the pyrometer readings on June 10, 1994.
Figure A.31: Billet temperature differentials and standard deviations plotted against average discharge temperatures on June 10, 1994.

Figure A.32: Billet temperature differentials and standard deviations plotted against minimum temperatures (east hearth block) on June 10, 1994.
Appendix B: Natural Gas and Combustion Air Orifice Plate Calculations for Company A

Gas flow calculations carried out at the company in 1976, 1978 and 1995 relied on orifice constants for both the natural gas and combustion air lines. The original specification sheets from North American Mfg. Co. for the natural gas lines were available, however, the combustion air orifice data could not be located. It was known that the orifices in the combustion air lines were annular in design. The combustion air and natural gas lines in the charge and heat zones are identical having the potential to deliver to sixteen burners. The soak zone lines have lower capacities since they deliver to twelve smaller burners (see Figure 5.1). The relevant data as specified by the manufacturer (converted to S.I. units) are summarized in Tables B.1 and B.2.

<table>
<thead>
<tr>
<th>Zone</th>
<th>No. of burners</th>
<th>Pipe I.D. (mm)</th>
<th>Bore diameter (mm)</th>
<th>Ratio</th>
<th>Orifice coeff. ((10^6 \text{ mm}^2))</th>
<th>Flow at 102 mm w.c. &amp; STP ((\text{m}^3/\text{h}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>16</td>
<td>206</td>
<td>138</td>
<td>0.666</td>
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<tr>
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<td>16</td>
<td>206</td>
<td>138</td>
<td>0.666</td>
<td>1.09</td>
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<tr>
<td>Soak</td>
<td>12</td>
<td>154</td>
<td>92</td>
<td>0.598</td>
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<td>849.5</td>
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Table B.1: Natural gas line data at STP (1 atm., 21°C and 635 mm w.c. line pressure)

<table>
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<tr>
<th>Zone</th>
<th>No. of burners</th>
<th>Pipe I.D. (mm)</th>
<th>Orifice coeff. ((10^6 \text{ mm}^2))</th>
<th>Flow at 102 mm w.c. &amp; STP ((\text{m}^3/\text{h}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>16</td>
<td>765</td>
<td>13.72</td>
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<tr>
<td>Heat</td>
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<td>765</td>
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<td>12</td>
<td>514</td>
<td>5.15</td>
<td>7,475.6</td>
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Table B.2: Combustion air line data at STP (1 atm., 21°C and 635 mm w.c. line pressure)

The orifice constants for the natural gas orifice plates were determined to be the product of the flow coefficient and the orifice area through which the gas flows.\(^5^7\) From reference [57], flow coefficient data was available for annular orifice ratios, which is defined as the ratio of the inner plate area to the inside area of the main pipe, of 0.7 to 0.9. For the heat and charge zone lines, this data had to be extrapolated to an orifice area ratio of 0.6 to produce the known orifice constant,
assuming it remained as a product of the flow coefficient and orifice area. At this value, the flow coefficient is 0.74. Similarly, the soak zone's area ratio is 0.65 giving a flow coefficient of 0.71. Because these area ratios are somewhat even values, it is felt that the orifice constants in the combustion air lines had been verified.

The gas densities were determined from the perfect gas law:

$$\rho_{gas} = \frac{MW_{gas} P_{total}}{RT}$$

(2.1)

where R is the universal gas constant, T is the gas temperature and P is the total pressure which is the sum of the barometric pressure and the static header pressure, the latter being approximately 889 mm w.c. The molecular weight of the gas, MW_{gas}, is calculated as a weighted average of the gas constituents obtained from the company: 86.76% CH₄, 8.69% C₂H₆, 0.32% C₃H₈ and 4.23% N₂.

The flow rate calculations use the relationship:

$$Q = KA \sqrt{\frac{2g\Delta p}{\rho_{gas}}}$$

(2.2)

The product KA is the orifice constant discussed above, g is the gravitational acceleration constant, and Δp is the pressure drop across the orifice measured by the Rosemount pressure transducers. Given a fuel composition, the percentage excess combustion air is defined as the difference between the supplied air and the theoretical air needed for combustion divided by the theoretical air and multiplied by 100%.

Calibration curves were generated for the conditions observed during the second plant trial campaign. For example, Figure B.1 is a calibration curve for the natural gas flow rates in the charge and heat zones as a function of pressure drop, which is measured at the company in inches of water column by the Rosemount pressure transducers. Figure B.2 shows the same calculations for the combustion air lines. Similar plots were generated for natural gas and combustion air flows.
in the soak zone lines and these are shown in Figures B.3 and B.4, respectively. From the data used to generate the gas flow calibration curves, it is then possible to generate a calibration curve that used the Rosemount readings for both the natural gas and the combustion air lines to give the percent excess combustion air. These plots, which are shown in Figures B.5 and B.6, enable the furnace operators to determine whether the prescribed firing strategy is being followed by examining the Rosemount pressure transducers.
Figure B.1: Example orifice plate calibration plots for natural gas in the charge and heat zones.

Figure B.2: Example orifice plate calibration plots for combustion air in the charge and heat zones.
Figure B.3: Example orifice plate calibration plots for natural gas in the soak zone.

Figure B.4: Example orifice plate calibration plots for combustion air in the soak zone.
Figure B.5: Percentage excess combustion air calculated from the measured pressures in the natural gas and combustion air lines in the charge and heat zones.

Figure B.6: Percentage excess combustion air calculated from the measured pressures in the natural gas and combustion air lines in the soak zone.
Appendix C: Logged Furnace Data from the Second Plant Trial Campaign at Company A - Feb. 2 to Feb. 6, 1995
Figure C.1: Average and maximum temperatures measured by the billet pyrometer at Company A on Feb. 2, 1995.

Figure C.2: Minimum temperatures measured by the billet pyrometer at Company A on Feb. 2, 1995.
Figure C.3: Measured and set-point temperatures for the charge zone on Feb. 2, 1995.

Figure C.4: Measured and set-point temperatures for the heat zone on Feb. 2, 1995.
Figure C.5: Measured and set-point temperatures for the soak zone on Feb. 2, 1995.

Figure C.6: Billet temperature differentials and standard deviations calculated from the pyrometer readings on Feb. 2, 1995.
Figure C.7: Billet temperature differentials and standard deviations plotted against average discharge temperatures on Feb. 2, 1995.

Figure C.8: Billet temperature differentials and standard deviations plotted against minimum temperatures (east hearth block) on Feb. 2, 1995.
Figure C.9: Average and maximum temperatures measured by the billet pyrometer at Company A on Feb. 3, 1995.

Figure C.10: Minimum temperatures measured by the billet pyrometer at Company A on Feb. 3, 1995.
Figure C.11: Measured and set-point temperatures for the charge zone on Feb. 3, 1995.

Figure C.12: Measured and set-point temperatures for the heat zone on Feb. 3, 1995.
Figure C.13: Measured and set-point temperatures for the soak zone on Feb. 3, 1995.

Figure C.14: Billet temperature differentials and standard deviations calculated from the pyrometer readings on Feb. 3, 1995.
Figure C.15: Billet temperature differentials and standard deviations plotted against average discharge temperatures on Feb. 3, 1995.

Figure C.16: Billet temperature differentials and standard deviations plotted against minimum temperatures (east hearth block) on Feb. 3, 1995.
Figure C.17: Average and maximum temperatures measured by the billet pyrometer at Company A on Feb. 4, 1995.

Figure C.18: Minimum temperatures measured by the billet pyrometer at Company A on Feb. 4, 1995.
Figure C.19: Measured and set-point temperatures for the charge zone on Feb. 4, 1995.

Figure C.20: Measured and set-point temperatures for the heat zone on Feb. 4, 1995.
Figure C.21: Measured and set-point temperatures for the soak zone on Feb. 4, 1995.

Figure C.22: Billet temperature differentials and standard deviations calculated from the pyrometer readings on Feb. 4, 1995.
Figure C.23: Billet temperature differentials and standard deviations plotted against average discharge temperatures on Feb. 4, 1995.

Figure C.24: Billet temperature differentials and standard deviations plotted against minimum temperatures (east hearth block) on Feb. 4, 1995.
Appendix D: Rougher Pulpit Data from Both Plant Trial Campaigns at Company B
Figure D.1: Furnace throughput and gas consumption recorded in the rougher pulpit for Feb. 28, 1994.

Figure D.2: Furnace throughput and gas consumption recorded in the rougher pulpit for March 1, 1994.
Figure D.3: Furnace throughput and gas consumption recorded in the rougher pulpit for March 2, 1994.

Figure D.4: Furnace throughput and gas consumption recorded in the rougher pulpit for March 3, 1994.
Figure D.5: Furnace throughput and gas consumption recorded in the rougher pulpit for March 4, 1994.

Figure D.6: Furnace throughput and gas consumption recorded in the rougher pulpit for Feb. 23, 1995.
Figure D.7: Furnace throughput and gas consumption recorded in the rougher pulpit for Feb. 24, 1995.

Figure D.8: Total natural gas consumption as a function of billet throughput for both plant trials at Company B. (1994 - 0.15 m billets, 1995 - 0.19 m billets)
Figure D.9: Natural gas consumption for Zone 1a as a function of billet throughput for both plant trials at Company B. (1994 - 0.15 m billets, 1995 - 0.19 m billets)

Figure D.10: Natural gas consumption for Zone 1b as a function of billet throughput for both plant trials at Company B. (1994 - 0.15 m billets, 1995 - 0.19 m billets)
Figure D.11: Natural gas consumption for Zone 2 as a function of billet throughput for both plant trials at Company B. (1994 - 0.15 m billets, 1995 - 0.19 m billets)

Figure D.12: Natural gas consumption for Zone 3 as a function of billet throughput for both plant trials at Company B. (1994 - 0.15 m billets, 1995 - 0.19 m billets)
Figure D.13: Natural gas consumption for Zone 4 as a function of billet throughput for both plant trials at Company B. (1994 - 0.15 m billets, 1995 - 0.19 m billets)

Figure D.14: Relationship between flue gas temperature and total natural gas consumption. (1994 - 0.15 m billets, 1995 - 0.19 m billets)
Figure D.15: Relationship between flue gas temperature and Zone 2 natural gas consumption. (1994 - 0.15 m billets, 1995 - 0.19 m billets)

Figure D.16: Relationship between waste gas temperature and total natural gas consumption. (1994 - 0.15 m billets, 1995 - 0.19 m billets)
Figure D.17: Relationship between combustion air temperature and total natural gas consumption. (1994 - 0.15 m billets, 1995 - 0.19 m billets)
Appendix E: Logged Furnace Data from the Second Plant Trial Campaign at Company B - Feb. 21-23, 1995
Figure E.1: Zone 1 measured and set-point temperatures recorded at Company B on Feb. 22, 1995.

Figure E.2: Zone 2 measured and set-point temperatures recorded at Company B on Feb. 22, 1995.
Figure E.3: Zone 3 measured and set-point temperatures recorded at Company B on Feb. 22, 1995.

Figure E.4: Zone 4 measured and set-point temperatures recorded at Company B on Feb. 22, 1995.
Figure E.5: Flue gas, waste gas and combustion air temperatures recorded at Company B on Feb. 22, 1995.

Figure E.6: Differential fuel consumption recorded at Company B on Feb. 22, 1995.
Figure E.7: Zone 1 measured and set-point temperatures recorded at Company B on Feb. 23, 1995.

Figure E.8: Zone 2 measured and set-point temperatures recorded at Company B on Feb. 23, 1995.
Figure E.9: Zone 3 measured and set-point temperatures recorded at Company B on Feb. 23, 1995.

Figure E.10: Zone 4 measured and set-point temperatures recorded at Company B on Feb. 23, 1995.
Figure E.11: Flue gas, waste gas and combustion air temperatures recorded at Company B on Feb. 23, 1995.

Figure E.12: Differential fuel consumption recorded at Company B on Feb. 23, 1995.
Figure E.13: Zone 1 measured and set-point temperatures recorded at Company B on Feb. 24, 1995.

Figure E.14: Zone 2 measured and set-point temperatures recorded at Company B on Feb. 24, 1995.
Figure E.15: Zone 3 measured and set-point temperatures recorded at Company B on Feb. 24, 1995.

Figure E.16: Zone 4 measured and set-point temperatures recorded at Company B on Feb. 24, 1995.
Figure E.17: Flue gas, waste gas and combustion air temperatures recorded at Company B on Feb. 24, 1995.

Figure E.18: Differential fuel consumption recorded at Company B on Feb. 24, 1995.
Appendix F: Billet Pyrometer Data from the Second Plant Trial Campaign at Company B - Feb. 21-23, 1995
Figure F.1: Billet pyrometer data recorded at Company B on Feb. 22, 1995.

Figure F.2: Billet pyrometer data recorded at Company B on Feb. 23, 1995.
Appendix G: Details of RFSIM.EXE

REVIEW.EXE

Configuration files used: VIEW.DAT, FUEL.DAT

This program calculates the direct and total exchange areas that are used by the Zone Method. These parameters are calculated only once for a given furnace and billet geometry. The program requires about 6 MB of memory and a typical execution time is approximately ten hours on a i486DX2-66. The total number of program lines coded in Fortran is about 3000 containing the following subroutines:

MAIN (main.for): Sets the common blocks and dynamic memory allocation. It then calls the next 9 subroutines in succession.

1.) INITIAL (init.for): The subroutine discretizes the furnace based on: furnace width, height and length, billet height, width and length, stroke distance, hearth block height and the length of the discharge ramp in the soak end of the furnace. For the furnaces in this study, the gas volumes match the locations of the burners. (Execution time on a i486-DX266: < 1 min.)

2.) COMBUST (combust.for): Using the data in FUEL.DAT, this subroutine evaluates the partial pressures of carbon dioxide and water vapor. The sum of these two partial pressures is then used in the following direct exchange area calculations. (time: < 1 min.)

3.) STOS (ss.for): This subroutine evaluates the surface-to-surface direct exchange areas. Usually ~10,000 rays between each surface pair are required for accuracies <2%. For each grey gas, the direct exchange areas are written into separate files labeled ss1-k0.prn, ss1-k1.prn, ss1-k2.prn and ss1-k3.prn. Similar files labeled ss3-????.prn represent summations that are used in ERROR and described below. (time: ~ 5 hours - depends on the number of surfaces and the accuracy desired)
4.) GTOS (gs.for): This subroutine evaluates the gas-to-surface direct exchange areas (and surface-to-gas direct exchange areas). It performs the calculation in a similar manner as the surface-to-surface direct exchange area code. The generated files are similar except that they are designated gs??????.prn. (time: ~ 5 hours - depends on the number of zones and the accuracy desired)

5.) GTOG (gg.for): This subroutine evaluates the gas-to-gas direct exchange areas. It performs the calculation in a similar manner as the surface-to-surface direct exchange area code. The generated files are similar except that they are designated gg??????.prn. (time: ~ 2 hours - depends on the number of gas zones and the accuracy desired)

6.) GTOSELF (ggself.for): This subroutine evaluates the direct exchange area for a gas zone radiating to itself. It performs the calculation in a similar manner as the surface-to-surface direct exchange area code. The generated files are similar except that they are designated ggself??????.prn. (time: ~ 1/2 hour - depends on the number of gas zones and the accuracy desired)

7.) ERROR (error.for): Summations described in Chapter 7 are calculated for the surface-surface, gas-surface, gas-gas and gas-self direct exchange area subroutines. The difference between calculated and actual surface areas, or gas volumes, gives an indication of the accuracy of the direct exchange areas (ERROR.PRN). (time: ~ 2 min.)

8.) TEXCH (texch.for): Based on the Zone Method, this subroutine calculates total exchange areas for each of the grey gases. The results are stored in a single file, TEXCH.DAT, in binary format in order to conserve disk space. Identities described in Chapter 7 are used to assess the errors that are recorded in TEAERR.PRN. (Time: ~ 5 min. - depends on the number of zones)
DATA FOR THE BILLET REHEAT FURNACE MODEL

Furnace dimensions (height(x), width(y), length(z), billet hgt, billet length, stroke, dz discharge
5.4 Furnace width (m)
0.91 Furnace height (m)
17.4 Furnace length (m)
0.5 Discharge ramp distance from soak end
0.0603 Hearth block height (m)
0.2667 Stroke distance
0.1524 Billet height (m)
0.1524 Billet width (m)
4.78 Billet length (m)

No. of axial zones on each surface
13 13 13 13 2 2
1 3 1 2 1 1

Elements on surface 1 - symmetry plane
1.47 1.28 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.35
0.6973

Elements on surface 2 - over-written by the billet discretization
1.47 1.28 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.35
1.35 0.04 0.31

Elements on surface 3 - wall
1.47 1.28 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.35
0.6973

Elements on surface 4 - roof
1.47 1.28 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.35
1.35 1.35

Elements on surface 5 - charge end
1.35 1.35
0.6973

Elements on surface 6 - soak end
1.35 1.35
0.6973

No. of gas volumes
2 1 3
1.47 1.28 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.33 1.35
1.35 1.35
0.6973

***********************************************************************
Extinction coefficients
0.4201
6.516
131.9
***********************************************************************

Surface-surface model control data (-ve icode start over)
Fine subdivisions percentage:
0.1

ICODE  KCW  DELC  DELF
1000  0.0000  0.25  0.125
1000  0.4201  0.25  0.125
1000  6.516  0.25  0.125
1000 131.9  0.25  0.125

***********************************************************************

Gas-surface model control data
ICODE  KCW  DELC  DELFS  DELSET
1000  0.4201  0.25  0.125  0.4
1000  6.516  0.25  0.125  0.25
1000 131.9  0.25  0.125  0.15

***********************************************************************

Gas-gas model control data

241
**Gas-to-self model control data**

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**Total exchange model control data**

4 - number of extinction coeffs.

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<tr>
<td>1000</td>
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<td>0.25</td>
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2 - number of burners per row
Fuel compositions expressed as fractions: AltaSteel

2 Number of burners per row (divided by two because of furnace symmetry)

6 Number of gas additions

Composition of gases:

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<th>No. 3</th>
<th>No. 4</th>
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<td>Nat. Gas</td>
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Temperature of gases:

293.0 293.0 293.0 293.0 293.0

Burner characteristics

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243
RFSIM.EXE

Configuration files used: FURNACE.DAT, FUEL.DAT and FIRING.DAT

For Company A’s furnace, this program requires about 10 MB of memory. The total number of program lines coded in Fortran is about 7900. A typical simulation lasts for eight hours on a i486-DX266 where the ratio of real time/simulation time is about 1.33. The program generates the following files: individual billet heating profiles, global energy balances, zone temperatures (gas, roof and wall), and "snapshots" of current furnace conditions.

MAIN (main.for): The MAIN program sets up the common blocks, initializes the model and controls the time-related iterations. It begins by setting up the required paths for input/output and reads in the data from TEXCH.DAT.

1.) INPUT (inout.for): This subroutine reads in the general simulation data from FURNACE.DAT including: stroke mode (single or double), simulation length, delay start and length, calibration data for comparison to thermocouples, nodal densities and characteristic dimensions for the billets, hearth, walls and roof. FURNACE.DAT also contains data used for furnace control but this remains as “work in progress”.

2.) FIRING (gasflow.for): This subroutine uses the current firing conditions to evaluate the energy released by combustion, the number of moles of each gas species and the excess oxygen used in each furnace control zone. It calculates the bulk movement of the products of combustion by assuming plug flow. The firing conditions are read from FIRING.DAT and contain the “data packets” described in Chapter 7.

3.) CHAMBER (chamber.for): Using the energy released from combustion, gas zone energy balances are evaluated using a Newton-Raphson iterative solver (hybrdl.for) to give the resulting gas temperatures and surface heat fluxes. The subroutine makes numerous calls to DIREX (directed exchange areas) to evaluate the furnace gas emissivities and absorptivities (which are also tem-
perature dependent). This part of the code requires about 50% of the total computing time.

4.) TRACK (track.for): Once the heat fluxes to the surrounding surfaces are determined the model enters the subroutine TRACK which regulates the movement of the charge. The billet temperatures are solved in three-dimensions using an ADI technique (BILLET3D - 3dadi.for) performing several calls to a tri-diagonal solver, TRIDAG. With a full furnace, this section of the code requires about 40% of the computing time. When a billet is discharged from the furnace, this subroutine updates the large global array that is used to store all of the billet temperatures. After calculations for all the billets and gaps have been completed, a heat flux profile for the top face of the hearth has been determined. New hearth temperatures are evaluated using a two-dimensional ADI scheme (2dadi.for + TRIDAG).

5.) WALLS (walls.for): The final subroutine entered by MAIN for each time step is WALLS (walls.for). This subroutine uses the heat fluxes calculated in CHAMBER to determine the temperature profiles through the side walls, end walls, roof and the section of refractory between the ends of the billets and the walls, or hearth channel. It is solved as a one-dimensional implicit technique and again calls TRIDAG.
**FURNACE.DAT**

**MODELLING PARAMETERS**

- No. of dim. for the billets (2 or 3): 3
- Iteration count for file flushing: 5
- Stroke mode: 1
- Use stored data? (1=yes, 0=no): 1
- Offset time to use for stored data: 200.0
- Model running time (min): 221.0
- Time at which to store s.s. data (min): 900.0
- Calibration time #1: 130.0
- Calibration time #2: 187.0
- Calibration nodes: (limited to five and based on T/C measurements)
  - 5 5 1
  - 5 2 1
  - 5 7 1
  - 2 5 1
  - 5 2 35

Hearth block 1:
- inside dist. from furnace c.l.: 0.55
- outside dist. from c.l.: 1.01

Hearth block 2:
- inside dist. from furnace c.l.: 1.64
- outside dist. from c.l.: 2.09

- Heffective for the skids: 75.0
- Coolant temperature: 30.0
- Locations for billet: 5.41
- contour data: 10.73

Dynamic firing data: Distance (m) | Temperature (°C) | Window (+/-)
--- | --- | ---
4.0 | 600.0 | 0.1
8.1 | 900.0 | 0.1
10.5 | 1051.0 | 0.1
13.35 | 1162.0 | 0.1
14.5 | 1200.0 | 0.1
16.4 | 1225.0 | 0.1

Material data:
- Billet data
  - Steel material id: 2
  - Nodes in billet width: 9
  - Nodes in billet height: 9
  - Nodes in billet length: 41

**HEARTH DATA**
- Hearth material id: 14
- Hearth length: 17.4
- Hearth thickness: 0.3
- MH: 601
- NH: 7

**WALL DATA**
- Wall material id: 13
- Roof material id: 15
- Nodes through wall thickness: 7
- Wall thickness: 0.3
- Roof thickness: 0.3

**HEAT TRANSFER COEFFICIENTS (W/m²-K)**
- Heat transfer coefficient to ambient: 15.0
- Ambient temperature: 25.0

**HYBRD1 PARAMETERS**
- Accuracy: 0.0001
- Log interval: 50

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**FIRING.DAT**

Gas order: natural, blast furnace, coke oven, combustion air, oxygen, leakage air

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<th>Total zone firing rates (m³/h)</th>
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