

## **Major Project-II**

# **ANALYSIS OF THERMAL LOADING FOR REHEATING FURNACE**

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**Master of Technology  
In  
Thermal Engineering**

By

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**(2K11/THE/07)**

UNDER THE SUPERVISION OF

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**July, 2014**

## **CANDIDATE'S DECLARATION**

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I hereby declare that the work which being present in the minor thesis entitled “**ANALYSIS OF THERMAL LOADING FOR REHEATING FURNACE**” in the partial fulfillment for the award of degree of MASTER OF TECHNOLOGY with specialization in “THERMAL ENGINEERING” submitted to Delhi Technological University, Delhi, is an authentic record of my own work carried out under the supervision of Dr. B.B.ARORA, associate. Prof., Department of Mechanical Engineering, Delhi Technological University . I have not submitted the matter in this dissertation for the award of any other Degree or Diploma or any other purpose what so ever.

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## **ACKNOWLEDGEMENT**

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It is a pleasure to acknowledge our gratitude to all the people involved, directly or indirectly in the completion of this project. I would like to thank our project guide **Dr.B.B. ARORA** who devoted valuable hours for this assignment and provided the motivational guidance during the entire preparation of this project, answering the number of technical queries despite his busy schedule. His valuable suggestions, constructive criticism and timely help proved extremely fruitful.

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**DEEPAK**

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## **ABSTRACT**

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Heat treating is the controlled heating and cooling of a material to achieve certain mechanical properties, such as hardness, strength and the reduction of residual stresses. Many heat treating processes require the precise control of temperature over the heating cycle. Typically, the energy used for process heating accounts for 2% to 15% of the total production cost. The objective of this work is “to analyze thermal loading for reheating furnace”. The research methodology was based on both experimental work and theoretical developments including modeling different types of heat treat furnaces. Experimental validations using the CHT model were conducted to identify the specific problems in the current model. An enhanced furnace model has been developed and validated. The new model takes into account the real time furnace parameters determined from the experimental data and accounts for furnace door opening and closing sequence.

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Heat treating is the controlled heating and cooling of a material to achieve certain mechanical properties, such as hardness, strength, flexibility, and the reduction of residual stresses. Many heat treating processes require the precise control of temperature over the heating cycle. Heat treating is used extensively in metals production, and in the tempering and annealing of glass and ceramics products. Typically, the energy used for process heating accounts for 2% to 15% of the total production cost. Thermal efficiencies can range from over 90% for condensing boilers to under 10% for small, batch operated, high temperature furnaces like heat treat furnaces [1]. In order to improve the energy efficiency and optimize the load throughput, it's vital to have numerical modeling capability to accurately simulate the heat treatment processes. Currently there are commercial solutions for modeling the heat transfer and material properties single work piece but none of them have a furnace model for simulating the thermal profile of the entire load. A comprehensive furnace model for different kinds of furnaces is crucial to accurately simulate the temperature of the load. Furnaces operate with efficiencies as low as 7% as against up to 90% achievable in other combustion equipment such as boiler. This is because of the high temperature at which the furnaces have to operate to meet the required demand. For example, a furnace heating the stock to 1200°C will have its exhaust gases leaving at least at 1200°C resulting in a huge heat loss through the stack. However, improvements in efficiencies have been brought about by methods such as preheating of stock, preheating of combustion air and other waste heat recovery systems.

### **Furnace Energy Supply**

Since the products of flue gases directly contact the stock, type of fuel chosen is of importance. For example, some materials will not tolerate sulphur in the fuel. Also use of solid fuels will generate particulate matter, which will interfere the stock place inside the furnace. Hence, vast majority of the furnaces use liquid fuel, gaseous fuel

or electricity as energy input. Melting furnaces for steel, cast iron use electricity in induction and arc furnaces. Non-ferrous melting utilizes oil as fuel.

### **Performance Evaluation of a Typical Furnace**

Thermal efficiency of process heating equipment, such as furnaces, ovens, heaters, and kilns is the ratio of heat delivered to a material and heat supplied to the heating equipment. The purpose of a heating process is to introduce a certain amount of thermal energy into a product, raising it to a certain temperature to prepare it for additional processing or change its properties. To carry this out, the product is heated in a furnace. This results in energy losses in different areas. For most heating equipment, a large amount of the heat supplied is wasted in the form of exhaust gases.

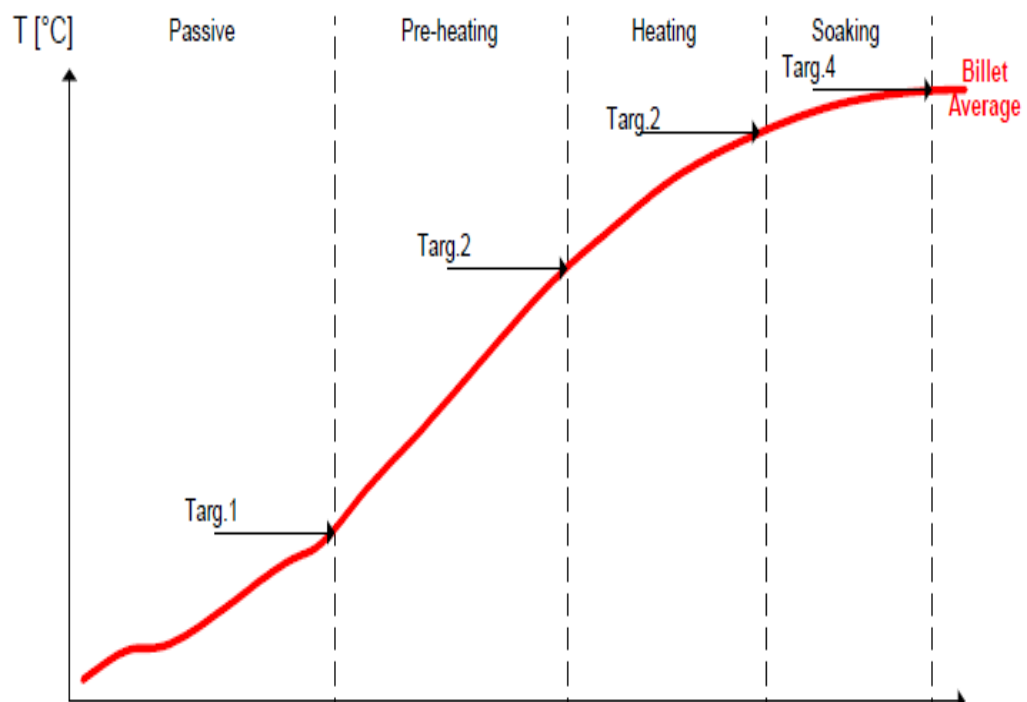
These furnace losses include:

- Heat storage in the furnace structure
- Losses from the furnace outside walls or structure
- Heat transported out of the furnace by the load conveyors, fixtures, trays, etc.
- Radiation losses from openings, hot exposed parts, etc.
- Heat carried by the cold air infiltration into the furnace
- Heat carried by the excess air used in the burners.

### **Nominal Temperature Level**

This is the temperature that the steel needs to be heated to give the required rolling performance. This temperature will depend to a great extent on the billet quality and mill horsepower available. It is essential that the furnace operator knows this temperature and the correct heating curve for the quality of steel being heated. There will be several grades of steel rolled in the mill and each of these grades will have a different heating profile. With the LTR (low temperature finishing rolling process), control of billet temperature from reheat furnace will be important. It is most important that the billets are heated uniformly from end to end and right through the

thickness. The furnace operator should be able to recognize temperature differentials, based on appearance of the heated billets. The furnace pressure control system maintains a slightly positive pressure at the discharge door by automatically adjusting the position of the waste gas damper to maintain a set point of near +0.06 mbar. The furnace pressure tap is located in the discharge zone South sidewall. The furnace pressure should be slightly positive at the discharge door opening at the skid level to keep cold air from entering the furnace. In this case the furnace pressure control has been designed with redundant pressure transmitters.



**Fig. 1.1 :** Heating Curve for reheating furnace

Decarburization, a process by which carbon atoms are taken out of the outside surfaces of the steel. A process occurring in carbon steels, when heated to sufficient temperature in an appropriate atmosphere.

1. Temperature: as temperature increases, the rate of decarburization increases  
decarburization does not take place under 800°C.

2. Time: the amount of decarburization increases with time. The duration that the steel surface is exposed to temperature increases the amount of decarburization.
3. Atmosphere: a major influence on decarburization is the atmosphere to which the steel is exposed.

### **1.1 Objectives and scope of study**

The objective of this work is to analyze thermal loading for reheating furnace. The current furnace model for continuous furnaces is studied in detail. It studies the different heat terms in the furnace model and how they are calculated. The research methodology was based on both experimental work and theoretical developments including modeling different types of heat treat furnaces. Experimental validations using the CHT model were conducted to identify the specific problems in the current model. From the experimental data and knowledge from the experiments, some improvements to the current furnace model are implemented and a new furnace model is developed and validated.

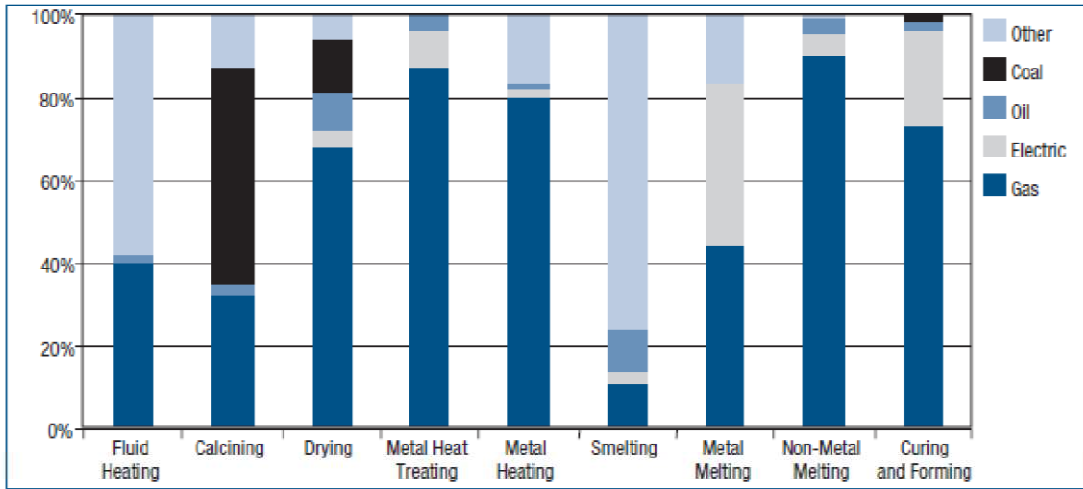
The main improvements include modeling thermal gradients present inside the furnace and accounting for heat loss arising due to the furnace door openings during loading and unloading of the furnaces. It is possible to accurately predict the thermal profile of the load inside a furnace using the improved furnace model. The new model enables us to improve the furnace efficiency by maximizing the load throughputs and save energy by accurately predicting the cycle time. The new model takes into account all the real time furnace parameters determined from the experimental data and accounts for some of the complex gradients and heating patterns that exist inside the furnace.

This chapter discusses the various researches done in modeling the heat treat furnaces and different software models available for performing the heat treat thermal simulation and their features and limitations.

### **2.1 HEAT TREATING PROCESS OVERVIEW**

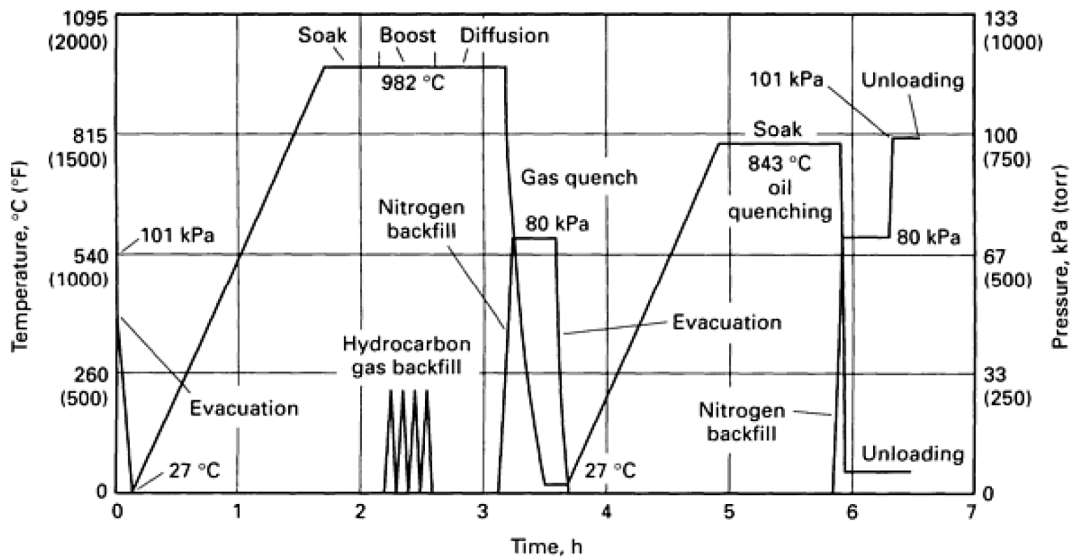
Heat Treatment may be defined as heating and cooling operations applied to metals and alloys in solid state so as to obtain the desired properties. Heat treatment is sometimes done inadvertently due to manufacturing processes that either heat or cool the metal such as welding or forming. Heat treatment is often associated with increasing the strength of material, but it can also be used to refine the grain size, relieve internal stress, to improve machinability and formability and to restore ductility after a cold working process. Some of the objectives of heat treatment are summarized as follows:

- Improvement in ductility
- Relieving internal stresses
- Refinement of grain size
- Increasing hardness or tensile strength
- Improvement in machinability
- Alteration in magnetic properties
- Modification of electrical conductivity
- Improvement in toughness



**Fig. 2.1 - Energy Source Breakdown for Key Industrial Process Heating Applications [2]**

The energy source for the heat treating industry is more than 80% from gas. Fig. 2.1 illustrates how fuels are used in several process heating applications. The costs of different fuel types can vary widely, which has a significant impact on the payback period of efficiency improvement projects. A heated work piece in a heat-treating furnace will undergo a given thermal schedule, typically, a heating soaking cooling cycle. (Fig. 2.2)



**Figure 2.2 – A typical heat treatment cycle for a typical carburizing process with a reheat cycle [3]**



### **2.1.1 Basic requirements of heat treatment process**

The main requirement of the heat treatment process is the accurate control of the temperature profile. And also soaking/holding at specified temperature for obtaining uniform cross section temperature across load and workpiece is another basic requirement of the heat treatment process. In processes like carburizing once the load reaches the soaking temperature the enriching hydrocarbon gas is added to the furnace and the load is held at the carburizing temperature for the carbon diffusion to occur until the required case depth is achieved. And the cooling cycle is determined by the required microstructure desired. And the cooling can be either liquid or gas cooling depending on the furnace.

### **2.1.2 Basic requirements of furnaces**

The main requirement of the furnaces in the heat treatment process is to provide the necessary heat input for the load/work piece. The furnace also requires a control system to control the temperature in the furnace accurately. Also a uniform temperature distribution is desired inside the furnace. Apart from the temperature controller there are also several atmosphere controllers and material handling controllers required based on the type of furnaces.

### **2.1.3 Heat treatment processes**

There are several different types of heat treatment processes. By controlling the soak temperature and the cool down rate of the steel, we can determine the process to be accomplished. Those processes include,

- Annealing
- Normalizing
- Stress relieving
- Hardening

- Tempering

### **Annealing**

Annealing is the process of heating the steel to a particular temperature in the austenite region and cooling down the steel very slowly. There are many derivatives of the annealing process, but generally the process is a slow cool process. Another derivative of the annealing process is known as sub-critical anneal. This process involves soaking at a temperature below the lower transformation line, in the region of 1,200°F to 1,300°F, until the steel has equalized across its cross-section in temperature, followed by a slow cool. Slow cooling can mean a cooling rate between 5°F per hour up to 50°F per hour.

### **Normalizing**

Normalizing is a process that makes the grain size normal. This process is usually carried out after forging, extrusion, drawing or heavy bending operations. When steel is heated to elevated temperatures to complete the above operations, the grain of the steel will grow. In other words, the steel experiences a phenomenon called "grain growth." This leaves the steel with a very coarse and erratic grain structure. Furthermore, when the steel is mechanically deformed by therefore mentioned operations, the grain becomes elongated. There are mechanical property changes that take place as a result of normalizing.

In as much as the normalized steel is soft, but not as soft as a fully annealed steel. Its grain structure is not as coarse as an annealed steel, simply because the cooling rate is faster than that of annealing. Usually the steel is cooled in still air and free from air drafts. The process temperature is virtually the same as for annealing, but the results are different due to the cooling rate.

## Stress relieving

Stress relieving is an intermediate heat treatment procedure to reduce induced residual stresses as a result of machining, fabrication and welding. The application of heat to the steel during its machining or fabrication will assist in removing residual stresses that will, unless addressed during the manufacturing by stress relieving, manifest themselves at the final heat treatment procedure. It is a relatively low temperature operation that is done in the ferrite region, which means that there is no phase change in the steel, only the reduction of residual stresses. The temperature region is usually between 800F to 1,300F. However, the higher that one goes in temperature, the greater the risk of surface oxidation there is. It is generally better to keep to the lower temperatures, particularly if the steel is a "pre-hard" steel. The hardness will be reduced if the stress relieve temperature exceeds the tempering temperature of the steel.

## 2.2 TYPES OF FURNACES

The furnaces used in the heat treating process can be classified in several different ways. The most popular classification method is shown in Fig. 2.3.

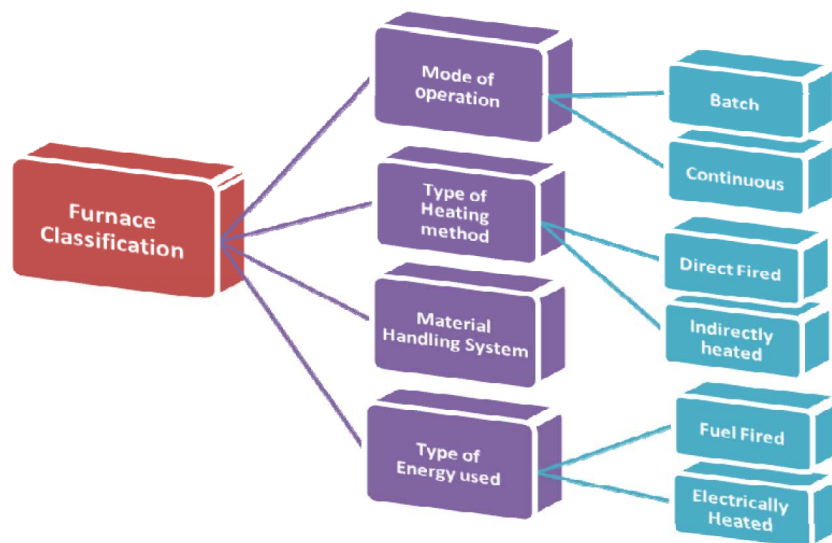


Figure 2.3 – Furnace Classification

### **2.2.1 Classification based on heating method**

One of the popular methods of classifying the furnaces is based upon the heating or energy input method. And it can be divided into combustion based heating and electric heating methods.

#### **Combustion-based (Fuel-based) Process Heating**

Heat is generated by the combustion of solid, liquid, or gaseous fuels, and transferred either directly or indirectly to the material. Common fuel types are fossil fuels (e.g. oil, natural gas, coal) The combustion gases can be either in contact with the material (direct heating), or be confined and thus be separated from the material (indirect heating; e.g., radiant burner tube, radiant panel, muffle).

#### **Electric process heating (Electro technologies)**

Electric currents or electromagnetic fields are used to heat the material. Direct heating methods generate heat within the work piece, by either (1) passing an electrical current through the material, (2) inducing an electrical current (“eddy current”) into the material, or (3) by exciting atoms/molecules within the material with electromagnetic radiation (e.g. microwave). Indirect heating methods use one of these three methods to heat a heating element or subsector, and transfer the heat either by conduction, convection, radiation or a combination of these to the work piece.

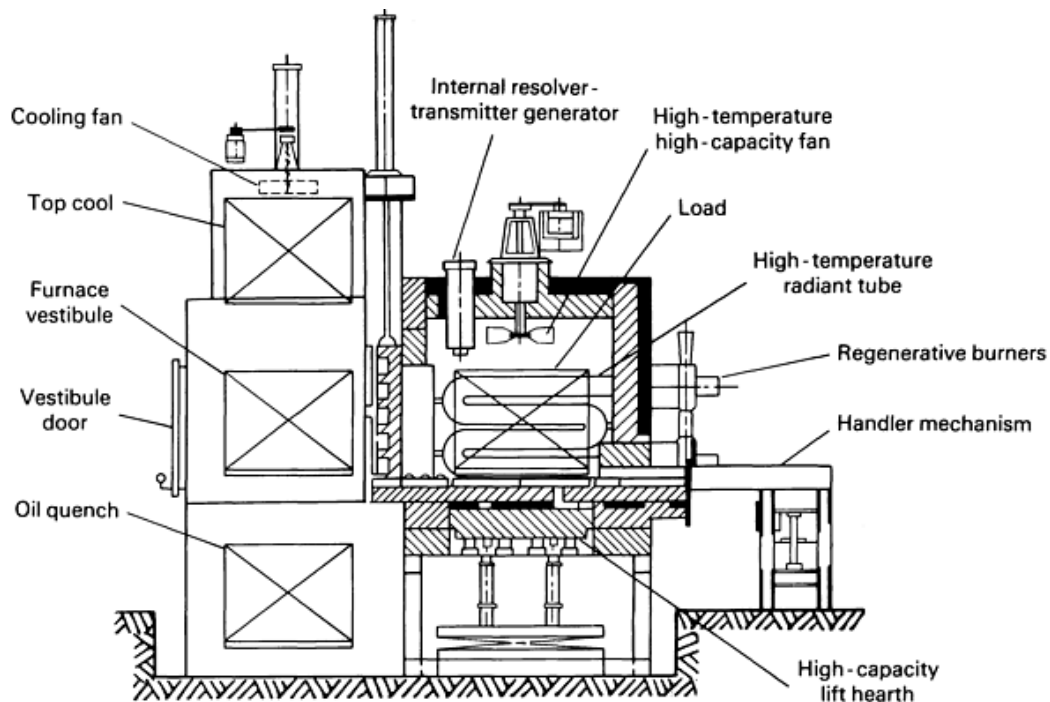
### **2.2.2 Classification based on mode of operation**

Another classification of the furnaces is based on the mode of operation. The classification is either a batch type operation or a continuous operation.

#### **Batch furnaces**

The basic batch furnace normally consists of an insulated chamber with an external reinforced steel shell, a heating system for the chamber, and one or more access doors to the heated chamber. Standard batch furnaces such as box, bell,

elevator, car bottom, and pit types are most commonly used when a wide variety of heat-hold-cool temperature cycles are required. Batch furnaces are normally used to heat treat low volumes of parts (in terms of weight per hour). Batch furnaces are also used to carburize parts that require heavy case depths and long cycle times. These furnaces are either electrically heated or gas/oil fired. The gas/oil fired furnaces can further be classified as direct fired and in-direct fired (radiant tube burners)



**Figure 2.4 - A schematic of Batch-Integral furnace**

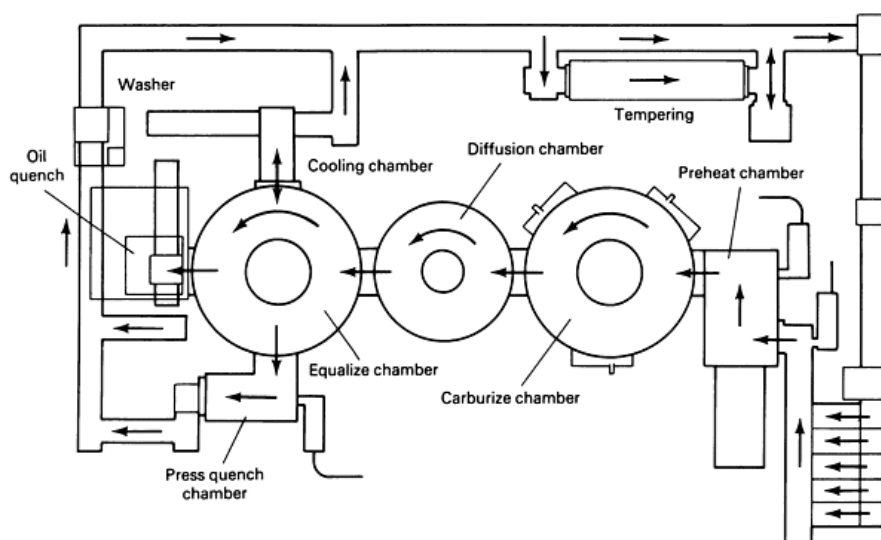
### **Vacuum furnaces (Type of batch furnace)**

In most heat-treating processes, when materials are heated, they react with atmospheric gases. If this reaction is undesirable, the work must be heated in the presence of some gas or gas mixture other than normal air. This is done in normal atmosphere furnace processing. The gas or gas mixture may be varied to cause desirable reactions with the material being processed or it may be adjusted so that no reactions occur. At different temperatures, different reactions may occur with the work and furnace atmosphere. In most atmosphere furnaces it is not possible to change the atmosphere

composition rapidly enough for optimum reactions or to control the atmosphere composition with the degree of precision required for some heat-treating processes. Vacuum furnaces allow gas changes to be made quite rapidly because they contain gases of low weight. Vacuum furnace technology removes most of the components associated with normal atmospheric air before and during the heating of the work. Fig. 2.2 shows a typical vacuum carburizing cycle with time and pressure v/s time plot.

### Continuous furnaces

Continuous furnaces consist of the same basic components as batch furnaces: an insulated chamber, heating system, and access doors. In continuous furnaces, however, the furnaces operate in uninterrupted cycles as the work pieces move through them. Consequently, continuous furnaces are readily adaptable to automation and thus are generally used for high-volume work. Another advantage of continuous furnaces is the precise repetition of time-temperature cycles, which are a function of the rate of travel through the various furnace zones. A multi chamber pusher-type continuous carburizing furnace system is widely used in industry where the heating, carburizing, and diffusion portions of the cycle are separated.



**Figure 2.5** - Pusher-type and rotary-hearth heat-treat system [5]

### 2.2.3 Classification based on material handling system

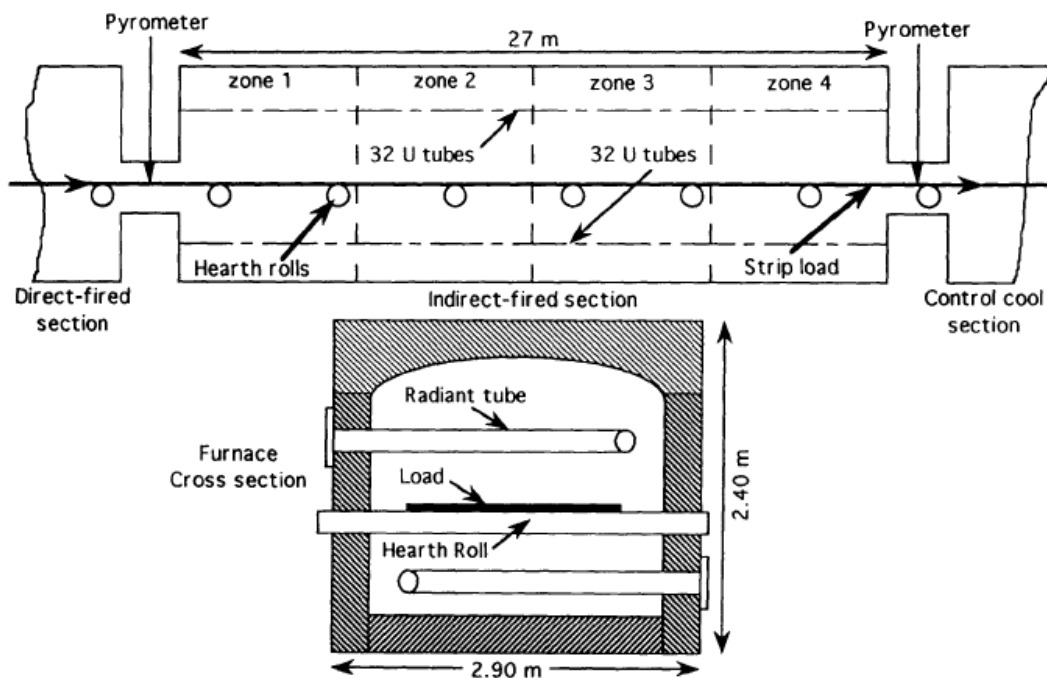
The selection of the material handling system depends on the properties of the material, the heating method employed, the preferred mode of operation (continuous, batch) and the type of energy used. An important characteristic of process heating equipment is how the load is moved in, handled, and moved out of the system.

Several important types of material handling systems are,

- Conveyor, Belts, Buckets, Rollers
- Rotary Hearth Furnaces
- Walking Beam Furnaces
- Pusher Type Furnaces
- Car Bottom Furnaces
- Continuous Strip Furnaces

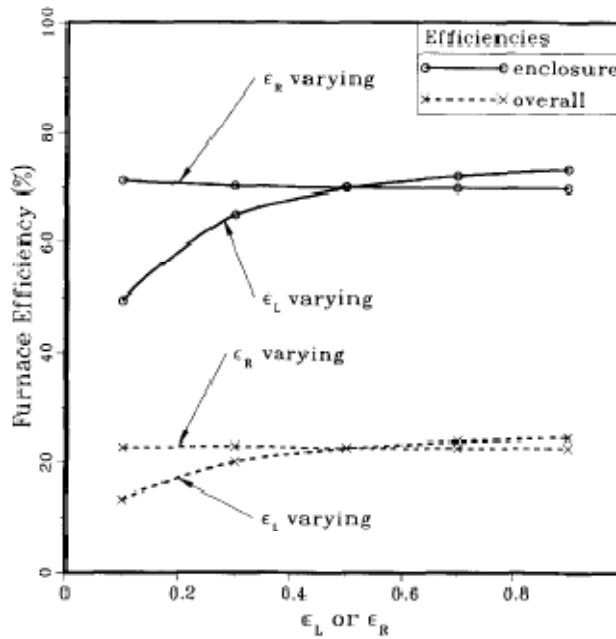
## FURNACE HEAT INPUT

### 2.3.1 Indirect fired (Radiant-tube) furnaces



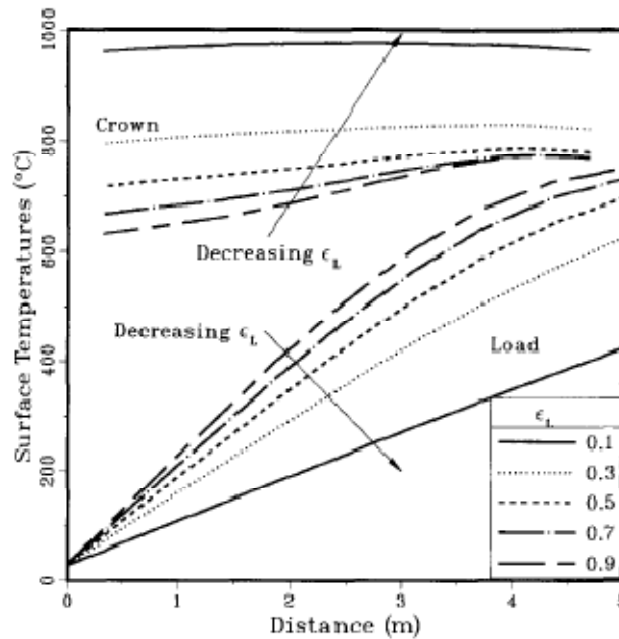
**Figure 2.6** - Schematic of the indirect-fired section of the Inland Steel annealing furnace [8]

A Thermal System Model for a Radiant-Tube Continuous Reheating Furnace' discusses about a thermal system mathematical model developed for a gas-fired radiant-tube continuous reheating furnace (Fig. 2.6). Are treated using a one-dimensional scheme, and the radiation exchange between the load, the radiant-tube surfaces, and the furnace refractories are analyzed using the radiosity method. The continuous furnace operation is simulated under steady-state conditions. The scope and flexibility of the model are assessed by performing parametric studies using furnace geometry, material properties, and operating conditions as input parameters in the model and predicting the thermal performance of the furnace. The various parameters studied include the effects of load and refractory emissivity (Fig. 2.7), load velocities, properties of the stock material [8].



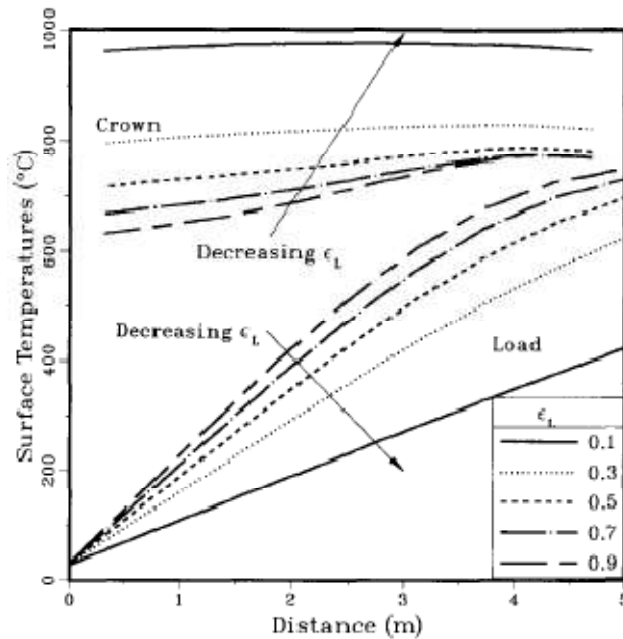
**Fig.2.7 (a)**-Variations in the furnace thermal efficiencies with load and refractory





**Figure 2.7(b)** - Variations in the load and roof surface temperatures with distance for varying load emissivity[8]

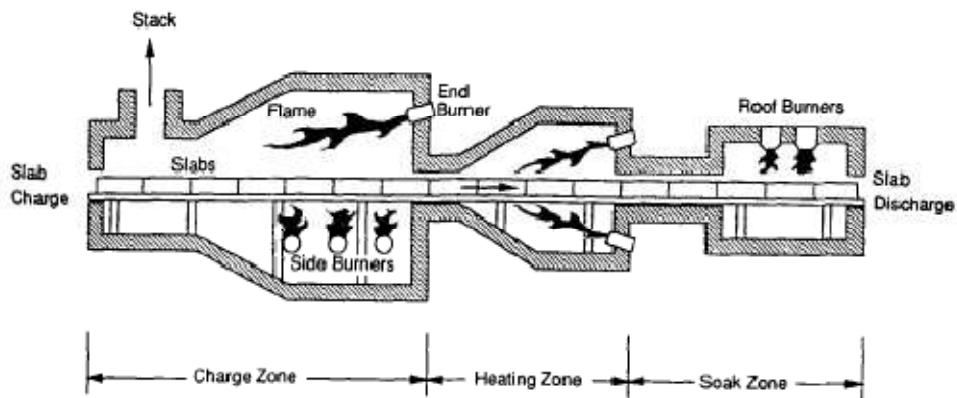
Another study is conducted to access the different types of radiant tube designs. Fig 2.8 which shows the variations in the load surface temperature for the same net fuel firing rate in the radiant tubes, indicates that the load surface temperatures are the highest for the W-type tube design, followed by the U-type and then the straight-through tubes. The lower load surface temperatures for the straight-through tubes in the furnace is due to the incomplete burning of fuel in the radiant tubes. A considerable amount of energy is lost in the form of unburned fuel at the exhaust of the straight-through tube. However, in the U-type and W-type tubes, further burning of the unburned fuel from the first branch takes place, resulting in a higher average tube wall temperature in the successive branches of the tube [8].



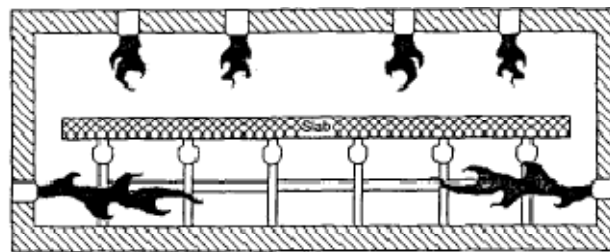
**Figure 2.8** -Variations in the load and crown surface temperature with distance for different radiant-tube designs in the furnace[8]

### 2.3.2 Direct fired furnaces

‘The Development, Verification, and Application of a Steady-State Thermal Model for the Pusher-Type Reheat Furnace’ outlines the development of a steady-state thermal model for the pusher-type steel reheating furnace. (Fig.2.9) commonly encountered energy consumption are analyzed. The objective of the work is to provide a means by problems with this furnace type like skid mark generation, scale formation, and high which furnace users might assess the effectiveness of changes to current operating practice, proposed furnace modifications, or new furnace designs in controlling these difficulties. The model is verified using data obtained in plant trials on several 32-m furnace reheating slabs, and model predictions for steel temperatures at six locations within the steel are compared with the experimental results. The inclusion of a hearth in



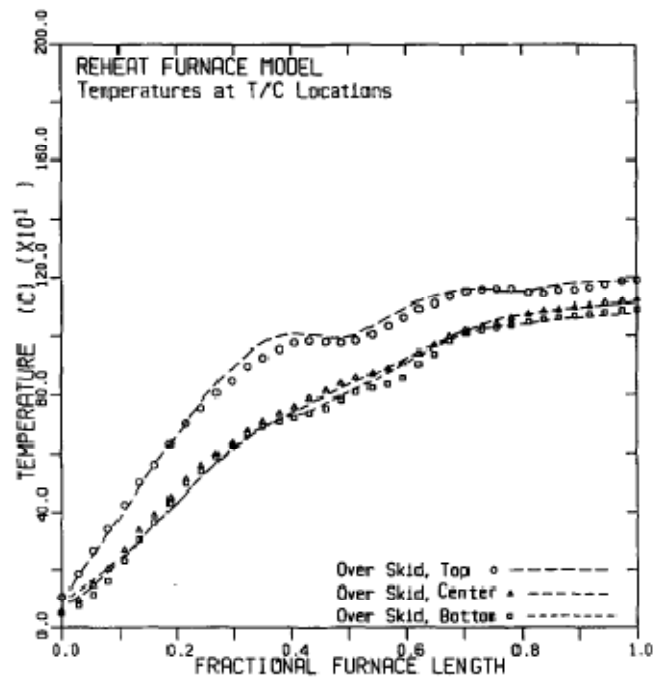
(a) Longitudinal section



(b) Transverse section

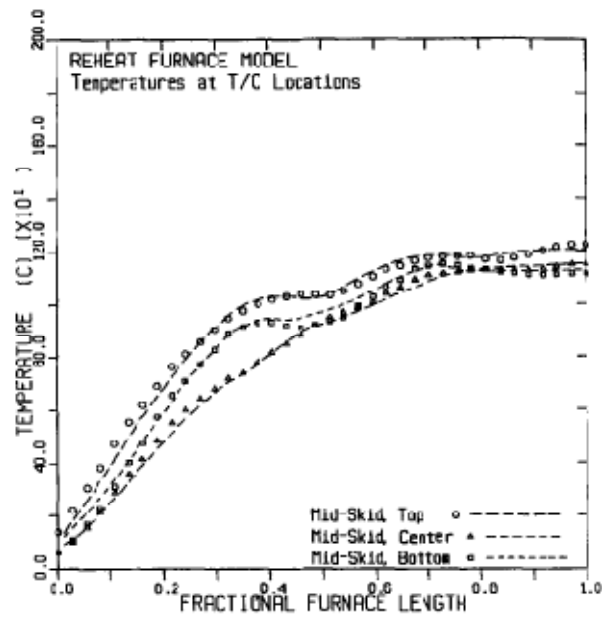
**Figure 2.9** -A typical pusher-type direct fired furnace: (a) longitudinal section, (b) transverse section [9].

the furnace soak zone was found to impose the least severe skid mark on the product, reducing the temperature variation over the bottom face from the level of 130 incurred by the best of the soak zone skid configurations examined, to the level of 85. The results suggest that, in the absence of a hearth section, the use of a well-insulated, cold-rider skid system over the majority of the furnace length, followed by a single offset of all skids occurring at the transition to a short section of hot-rider skids near the furnace discharge, is sufficient to suppress the final skid mark to a level very close to the minimum achievable with that particular skid design. When assessed on the basis of minimizing both the final skid mark and the energy loss to the skid system, this configuration was found to be the best of the skid layouts examined.



(a)

**Figure 2.10 - (a)** A comparison of model predictions for steel temperature and plant data at between-skid thermocouple locations.



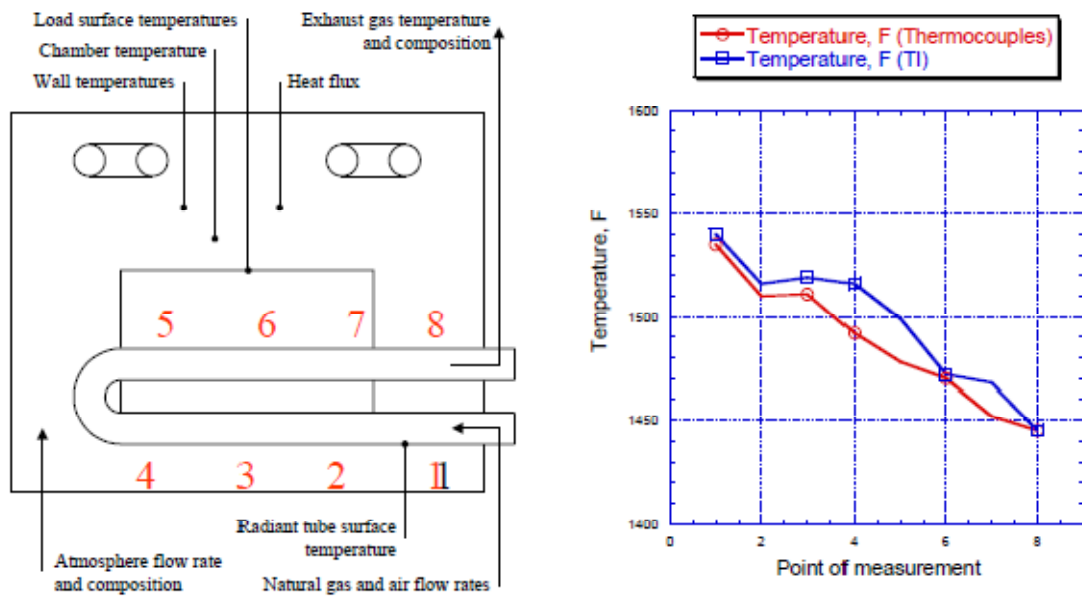
(b)

**Figure 2.10 (b)** A comparison of model predictions for steel temperature and plant data at over-skid thermocouple locations[9].

‘Modeling and Parametric Studies of Heat Transfer in a Direct-Fired Continuous Reheating Furnace’ - is a mathematical system model of a direct-fired continuous reheating furnace. The furnace is modeled as several well-stirred gas zones with one-dimensional (1-D) heat conduction in the refractory walls and two-dimensional heat transfer in the load. The convective heat-transfer rate to the load and refractory surfaces are calculated using existing correlations from the literature. Radiative heat exchange within the furnace is calculated using Hotel’s zone method by considering the radiant energy exchange between the load, the combustion gases, and the refractories. The mongrel characteristics of the combustion gases are considered by using a four-gray gas model to treat the mixture as a radiatively participating medium. The parametric investigations included in this paper study the effects of the load and refractory emissivity and the height of the combustion space on the thermal performance of the furnace.

## **2.4 FURNACE CONTROL**

Thermal imaging control of furnaces and combustors developed by Gas Technology Institute [6]. The objective of this project is to demonstrate and bring to commercial readiness a near infrared thermal imaging control system for high temperature furnaces and combustors. The concept used in this project is to provide improved control to high temperature furnaces using a near-IR thermal imaging control system. Initial stages of the Thermal Imaging sensor hardware development were conducted by testing on a laboratory electric furnace. The complete system was then tested on a GTI heat treat furnace. A state-of-the-art control system was installed and accepted input for control from the thermal imaging system.



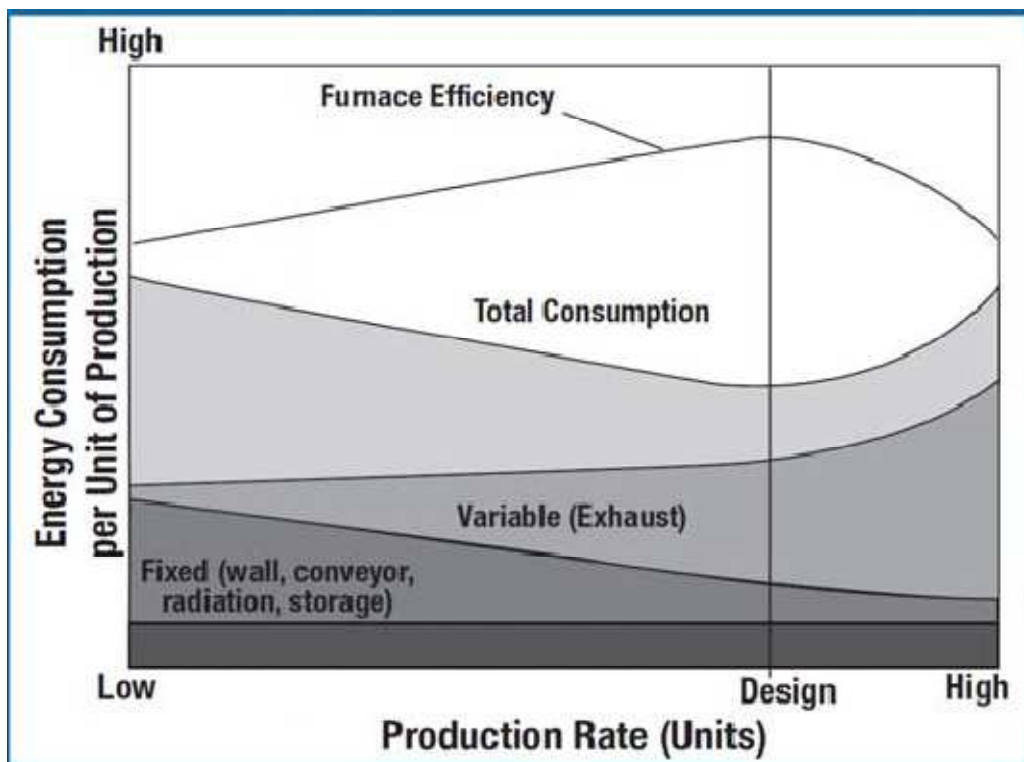
**Figure 2.11** -Comparison of the thermocouples with the thermal imaging system and the thermal gradient inside the box type furnace [6]

The project strategy is to input the thermal imaging system data into a set of control system algorithms that would give secondary control instructions to burners (air-fuel ratios, etc.) for tuning control.

## 2.5 THE NEED TO MODEL FURNACES

A commonly overlooked factor in energy efficiency is scheduling and loading of the furnace. “Loading” refers to the amount of material processed through the furnace in a given period of time. It can have a significant effect on the furnace's energy consumption when measured as energy used per unit of production (Btu/lb). Certain furnace losses (wall, storage, conveyor and radiation) are essentially constant regardless of production volume; therefore, at reduced throughputs, each unit of production has to carry a higher burden of these fixed losses. Flue gas losses, on the other hand, are variable and tend to increase gradually with production volume. If the furnace is pushed past its design rating, flue gas losses increase more rapidly, because the furnace must be operated at a higher temperature than normal to keep up

with production. Total energy consumption per unit of production will follow the curve in Fig. 2.12, which shows the lowest at 100% of furnace capacity and progressively higher the farther throughputs deviate from 100%. Furnace efficiency varies inversely with the total energy consumption. The lesson here is that furnace operating schedules and load sizes should be selected to keep the furnace operating as near to 100% capacity as possible. Idle and partially loaded furnaces are less efficient



**Figure 2.12** -Impact of production rate on energy consumption per unit of production[2].

In order to achieve maximum efficiency it is required to design the furnace part load to the maximum furnace capacity. A numerical tool with a furnace model helps to achieve this goal. Also another important quality metric in the heat treatment processes is soak time (amount of time a load stays at a given temperature) A furnace model with work piece thermal profile prediction can accurately predict the time required to reach the process temperature and the soak time. So the process can be

accurately designed eliminating guesses and removing conservative recipes.

## **2.6 CURRENT RESEARCH**

The current research to model the heat treatment process is focused mostly on a single part model using the commercially available FEM software tools. The topics discussed in chapters 2.3.1 and 2.3.2 are the research conducted by E.S Chapman et al and it focuses on using the FEM method with temperature boundary conditions [9].

### **Limitations**

The major limitations of the single part model and the FEM based model are the determination of the temperature boundary condition. The temperature boundary condition is an important input for the model and the results are dependent on the accuracy of the boundary conditions. Every furnace is unique in the heat treatment industry so it's difficult to determine the boundary condition without a comprehensive furnace model. Currently none of the research is focused on the furnace model. Also FEM based approach is a computation intensive and consumes several hours for calculating results.

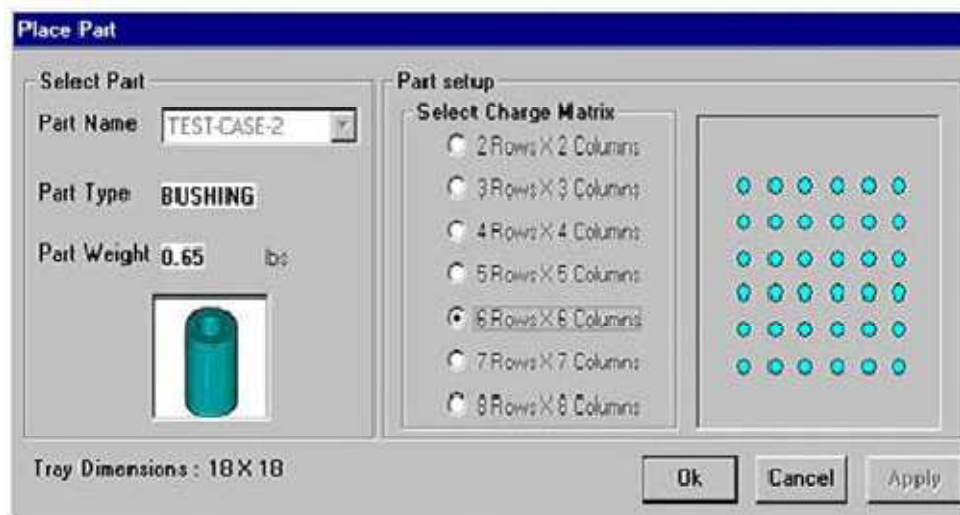
## **2.7 CURRENT SOFTWARE TOOLS**

Process Heating Assessment and Survey Tool (PHAST) - is a software tool developed at DOE for identifying methods to improve thermal efficiency of heating equipment. This tool helps industrial users survey process heating equipment that consumes fuel, steam, or electricity, and identifies the most energy-intensive equipment. Use the tool to compare performance of equipment under various operating conditions and test "what-if" scenarios. PHAST constructs a detailed heat balance for selected pieces of process heating equipment. The process considers all areas of the equipment in which energy is used, lost, or wasted. Results of the heat balance pinpoint areas of the equipment in which energy is wasted or used



unproductively.

FurnXpert program is developed to optimize furnace design and operation. The program mainly focuses on the heat balance of the furnace. The load pattern is just aligned load pattern with one layer and it cannot deal with the condition of work pieces loaded in the fixtures. While, in this condition the work pieces inside the fixture are heated by adjacent work pieces, not directly by furnace. Figure 2.13 shows an interface of load pattern specifications in FurnXpert. The result curves are shown in Figure 2.14



**Figure 2.13 - The load pattern for continuous belt in FurnXpert software [10]**

SYSWELD, published by the ESI group is another tool for the simulation of heat treatment, welding and welding assembly processes, taking into account all aspects of material behavior, design and process. It can perform FEA on any part geometry that can be modeled through the modeling component, and can be expanded to include additional process data that has already been obtained through experimentation to generate accurate results. SYSWELD simulates all usual heat treatment processes like bulk hardening, tempering and hardening, treatment with boron, thermo-chemical treatment like case hardening, carbonitriding, nitriding and nitro-carburising. It can

also simulate Surface hardening processes like laser beam hardening, Induction hardening, electron beam hardening, plasma beam hardening, friction hardening and flame hardening.



**Figure 2.14** - The result illustration of FurnXpert software [10]

The software computes distortions of parts, residual stresses, plastic strains and the yield strength depending on the mixture of phases of the material in use both during and at the end of the heat treatment process, plus the hardness at the end of the process. But the input for the software has to be generated by the user and need to determine the furnace boundary conditions.

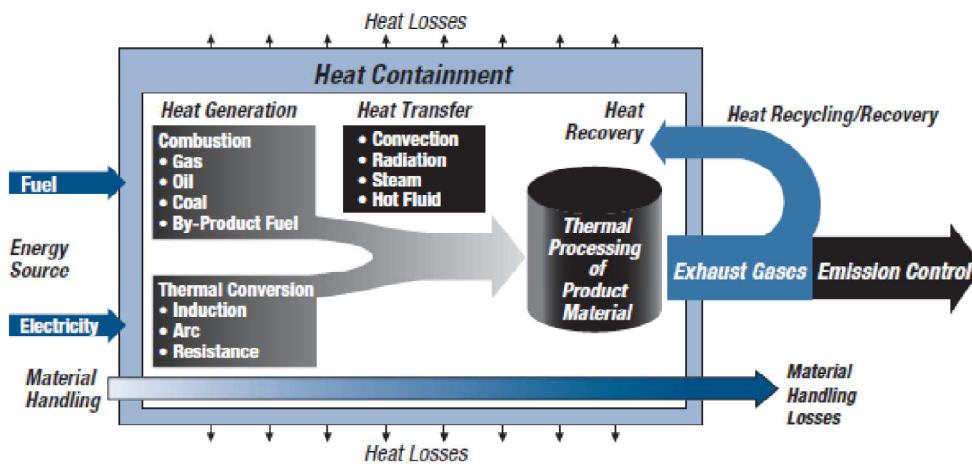
## **2.8 SUMMARY**

Heat treatment is an important manufacturing process. The furnace is key element in the heat treat process. The heat treat process variations can often be attributed to temperature variations in the process. So a tight control of temperature during the process is key to achieve minimum part variations during heat treatment. Also the modeling study is very limited. The current research is focused mostly on Finite Element Analysis based approach. And all the tools predict the microstructure and material properties for a given work piece. The key input for these tools is the thermal profile of the heat treat process and there is no comprehensive solution currently available.

**3.1 Overview of current Computerized Heat Treatment (CHT) furnace model**

Common to all process heating systems is the transfer of energy to the material to be heat treated. Direct heating methods generate heat within the material itself (microwave, induction, controlled exothermic reaction), whereas indirect methods transfer energy from a heat source to the material by conduction, convection, radiation, or a combination of these functions. In most processes, an enclosure is needed to isolate the heating process and the environment from each other. Functions of the enclosure include, but are not restricted to, the containment of radiation (microwave, infrared), the confinement of combustion gases and volatiles, the containment of the material itself, the control of the atmosphere surrounding the material, and combinations thereof. Common industrial heat treat process heating systems fall in one of the following categories:

- Combustion-based process heating systems
- Electric process heating systems



**Figure 3.1 - Key components of a process heating system [15]**

Temperature control is one of the most important aspects in heat treatment process. Heat treatment temperature mainly refers to soaking temperature and time. The soak temperature and time significantly affect the material properties of parts. The furnace productivity and efficiency are maximized by aggressive part load design and optimum thermal schedules.

Currently in the industry part load design is determined based on experience and empirical rules. With the advent of several heat transfer simulation tools it is now possible to simulate heat transfer of the work pieces in a furnace. Although there are a lot of commercial FEA tools available for simulation they all require a boundary condition for the simulation. Determining the boundary condition is difficult as it involves a complex furnace model.

The CHT software was developed for predicting the thermal profiles of the parts inside a furnace based on a hybrid FDM and empirical solution. The core of the software is the furnace model that was developed based on several empirical equations determined through experiments and knowledge and expertise derived from the furnace manufacturers. To accurately calculate the part temperature it is important to calculate the furnace temperature and heat balance in the furnace. Figure 3.2 shows the flow chart for the calculation of furnace temperature using the CHT furnace model.

The CHT furnace model can be divided into furnace energy balance model, heat transfer model and furnace control model.

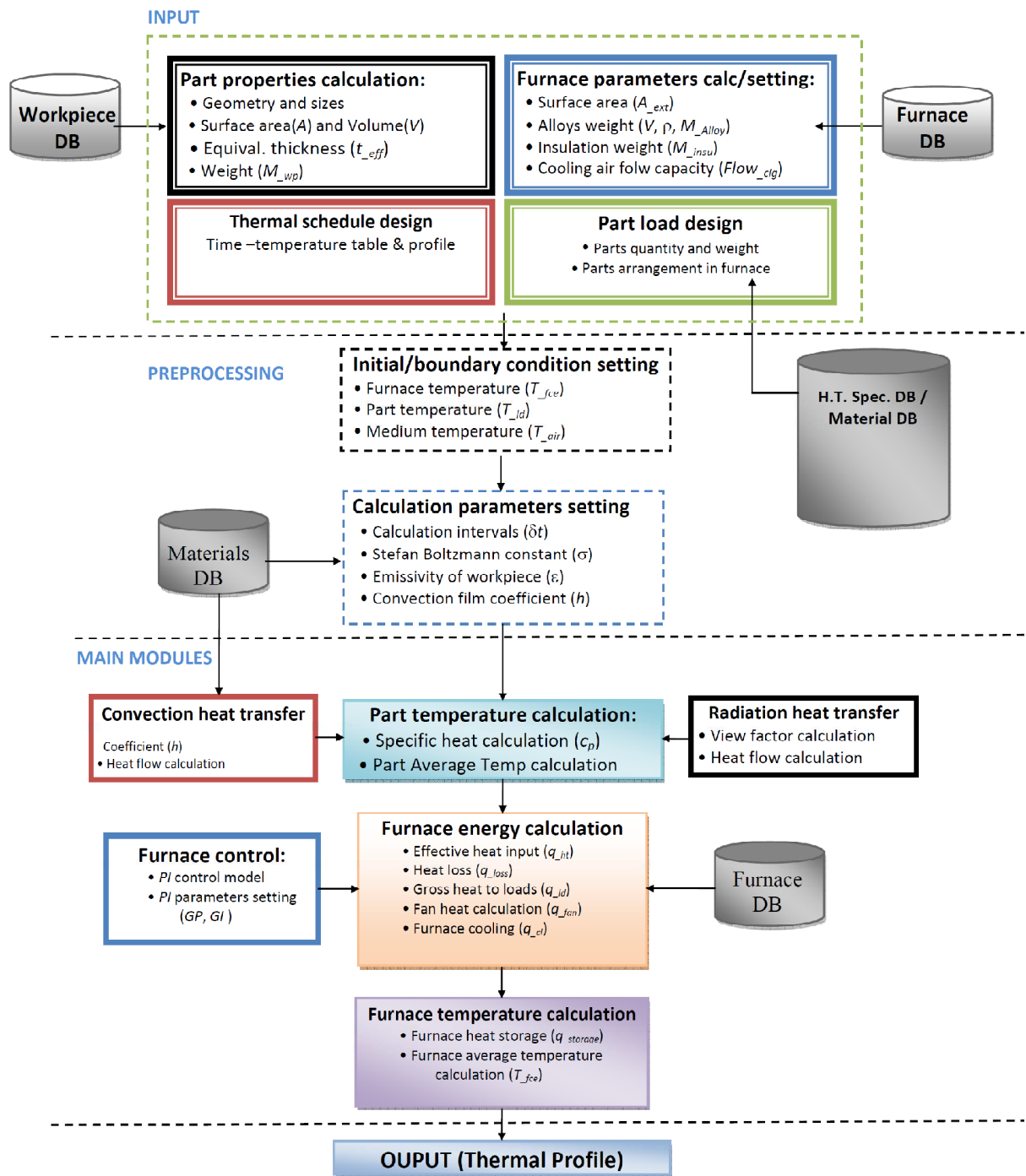


Figure 3.2 - Flowchart for temperature calculation of loaded furnace

### 3.2 Furnace energy balance model

Heat storage is calculated according to the energy balance,

(Heat storage) ~ Function of [(Available heat), (Heat to load),(Wall losses), (Radiation losses)] (Available Heat) ~ Function of (Gross input)

**Table 3.1** - Energy terms and their definitions[11]

Energy Items	Definitions
Gross Input	The total amount of heat used by the furnace.
Available Heat	Heat that is available to the furnace and its workload, including work piece, furnace structural components, accessories, and heat losses due to furnace itself.
Heat to Load	Heat that ultimately reaches the product in the furnace.
Wall Losses	Heat conducted out through the furnace walls, roof and floor due to the temperature difference between inside and outside.
Radiation Losses	Heat lost from the furnace as radiant energy escaping through openings in walls, doors, etc.
Heat Storage	Heat absorbed by the insulation and structural components of the furnace to raise them to operating temperature.

$$q_{storage} = q_{ht} - q_{ld} - q_{loss} - q_{air} + q_{fan} \quad (3.1)$$

where  $q_{ht}$  is effective heat input;  $q_{loss}$  is heat loss;  $q_{ld}$  is the heat to the work pieces;  $q_{air}$  is heat absorbed by atmosphere; and  $q_{fan}$  is the heat input effect created due to the increase in convection by fan.

### 3.2.1 Energy terms calculation (Indirect gas-fired batch furnace)

**Effective heat input ( $q_{ht}$ ) :**

$$q_{ht} = Htg \cdot AHC \cdot q_{conn} \quad (3.2)$$

where Htg is an adjust coefficient for heat input. The calculation will be given in the next section.

AHC is the corrected coefficient to the gross heat input

$$AHC = AH1 + AH2 + AH3 \quad (3.3)$$

where, the values AH, AH2 & AH3 are based on the experimental data:



**Heat to load (q<sub>ld</sub>):**

The heat to load, is mainly subjected to the hybrid convection and radiation heat transfer. It can be calculated using the following equation:

$$q_{ld} = k_{ld} \cdot \left( \frac{dT_{ld}}{dt} \right) = h \cdot (T_{fce} - T_{ld}) + \sigma \cdot \epsilon \cdot (T_{fce}^4 - T_{ld}^4) \quad (3.4)$$

**Heat loss (q<sub>loss</sub>):**

Heat loss depends on the design factor for the heat loss of furnace and the surface area of furnace. Following is an empirical equation:

$$q_{loss} = DF \cdot (Q_{loss\_wall} + Q_{loss\_rad}) \quad (3.5)$$

where, DF is the design factor, and A<sub>ext</sub> is the surface area of furnace.

**Furnace wall losses:**

$$Q_{loss\_wall} = A_{fce} \times f(T_{fce}) \quad (3.6)$$

where A<sub>fce</sub> is furnace wall area (inside); f(T<sub>fce</sub>) is a function for heat loss, in Btu/ft<sup>2</sup>-hr. Typical heat loss data are tabulated in Table 3.2

**Radiation losses:**

$$Q_{loss\_rad} = A_{open} \cdot \sigma \cdot (T_{gas}^4 - T_{amb}^4) \quad (3.7)$$

where, Q<sub>loss\_rad</sub> is the radiation losses, A<sub>open</sub> is the opening area, T<sub>gas</sub> is the temperature of furnace gas, T<sub>amb</sub> is the temperature of ambient outside furnace, σ is Stefan-Boltzmann constant.

**Table 3.2 - Heat loss for different furnace walls construction (Btu/hr-ft<sup>2</sup>)[11]**

Wall Construction	Hot Face Temperature, °F							
	1000	1200	1400	1600	1800	2000	2200	2400
9" Hard Firebrick	550	705	862	1030	1200	1375	1570	1768
9" Hard Firebrick + 4.5" 2300° Insulating F.B.	130	168	228	251	296	341	390	447
9" Hard Firebrick + 4.5" 2000° Insulating F.B. + 2" Block Insulation	111	128	155	185	209	244	282	325
4.5" 2000° Insulating F.B.	185	237	300	365	440	521	-	-
9" 2000° Insulating F.B.	95	124	159	189	225	266		
9" 2800° Insulating F.B.	142	178	218	264	312	362	416	474
9" 2800° Insulating F.B. + 4.5" 2000° Insulating F.B.	115	140	167	197	232	272	307	347
9" 2800° Insulating F.B. + 4.5" 2000° Insulating F.B. + 2" Block Insulation	71	91	112	134	154	184	204	230
9" 2800° Insulating F.B. + 3" Block Insulation	114	142	172	201	232	264	298	333
8" Ceramic Fiber – Stacked Strips, 8 #/cu ft Density	27	45	64	86	114	146	178	216
10" Ceramic Fiber – Stacked Strips, 8 #/cu ft Density	16	35	54	76	94	120	142	172
12" Ceramic Fiber – Stacked Strips, 8 #/cu ft Density	13	27	43	60	79	98	118	143
9" Hard Firebrick + 3" Ceramic Fiber Veneer, 8 #/cu ft Density	177	240	309	383	463	642	721	800
9" 2800° Insulating F.B. + 3" Ceramic Fiber Veneer, 8 #/cu ft Density	102	125	151	183	227	274	325	408

**Fan heat input effect ( $q_{fan}$ ):**

It is calculated based on an empirical equation:

$$q_{fan} = HP_{fan} \left( \frac{520}{460 + T_{fce}} \right)$$

where,  $HP_{fan}$  is the horsepower of re-circulating fan.

**Heat absorbed by air ( $q_{air}$ )**

$$q_{air} = Clg \cdot Flow_{air} \cdot \rho \cdot Cp \cdot (T_{fce} - T_{air}) \quad (3.9)$$

where  $Clg$  is the PID control variable,

Flow  $air$  is the airflow heated by the fuel gas and it equals to

$$Flow_{air} = \frac{Q_{Gross}}{hv} \cdot R \cdot (1 + xs_{air}) \quad (3.10)$$

where  $hv$  is the gross heating value of commercial fuel gases, as listed in Table 3.3;  $R$  is the stoichiometric air/gas ratio, listed in Table 3.3;  $Q_{gross}$  is the gross heat input;  $xs_{air}$  is the combustion excess air;  $\rho$  is air density;  $cp$  is the air specific heat;  $T_{fce}$  is the furnace temperature; and  $T_{air}$  is the air temperature before mixed enter furnace.

**Table 3.3** - Combustion properties of typical commercial fuel gases[11]

Gas type	Heating value (Btu/ft3)	Heating value (Btu/lb)	Air/Gas Ratio (ft3 air/ft3 gas)	Air/Gas Ratio (lb air/lb gas)
Acetylene	1498	21,569	11.91	13.26
Hydrogen	325	61,084	2.38	33.79
Butane (natural gas)	3225	21,640	30.47	15.63
Butylene (Butene)	3077	20,780	28.59	14.77
Carbon Monoxide	323	4368	3.38	2.46
Carburetted Water Gas	550	11,440	4.6	7.36
Ethane	1783	22,198	16.68	15.98
Methane	1011	23,811	9.53	17.23
Natural (Birmingham, AL)	1002	21,844	9.41	15.68
Natural (Pittsburgh, PA)	1129	24,161	10.58	17.31
Natural (Los Angeles, CA)	1073	20,065	10.05	14.26
Natural (Kansas City, MO)	974	20,259	9.31	14.59
Natural (Groningen, Netherlands)	941	19,599	8.41	13.45
Propane (natural gas)	2572	21,500	23.82	15.37
Propylene (Propene)	2322	20,990	21.44	14.77

### 3.2.2 Heat balance in continuous furnace

The calculation deals with static condition. Therefore the heat balance is dynamic. It is assumed furnace temperature doesn't vary to load changes. So the heat storage in the furnace need not be calculated. The heat terms only refer to the heat input, heat absorption by the load and moving accessories and heat loss. The furnace structure and accessories are classified into two types: moving and fixed/shaking. The moving

accessories take away heat while the fixed or shaking accessories do not take away heat.

### Heat balance in each zone:

The dynamic heat balance is

$$Q_{input\_p} + Q_{fan\_p} = Q_{load\_p} + Q_{fix\_p} + Q_{belt\_p} + Q_{wall\ loss\_p} + Q_{zone\_p} + Q_{shell\_cooling\_p}$$

$Q_{input\_p}$  - the heat input by furnace

$Q_{fan\_p}$  - the heat input by fan

$Q_{load\_p}$  -the heat absorption by load

$Q_{fix\_p}$  -the heat absorption by fixture

$Q_{belt\_p}$  -the heat absorption by belt

$Q_{wall\ loss\_p}$  -the heat loss from furnace wall

$Q_{zone\_p}$  -the heat transfer between zones and heat loss from the end zones

$Q_{shell\_cooling\_p}$  - the heat absorption by shell cooling water

From the above equation the heat input by furnace can be calculated indirectly as follows,

$$Q_{input\_p} = Q_{load\_p} + Q_{fix\_p} + Q_{belt\_p} + Q_{wall\ loss\_p} + Q_{zone\_p} + Q_{shell\_cooling\_p} - Q_{fan\_p} \quad (3.12)$$

It is compared with the power of the furnace to see if it exceeds the power, which means the heat balance cannot be maintained. So the furnace temperature control system such as PID is not considered.

The heat balance is calculated when a cycle is finished. Then the heat absorption in each zone is calculated based on the relationship between calculation domain and zone length. These heat terms are the functions of furnace temperature. The furnace temperature is adjusted to maintain the heat balance. The heat input should also be calculated directly by the connected heat input and the available heat coefficient.

### Energy terms calculation

In the following equations, p refers to furnace zone number, i,j,k refers to workpiece number, m refers to time constant. The following equations discuss the heat balance in each zone during a time step delta t.

#### Heat absorbed by the load:

$$Q_{load\_p} = C_{load\_p} \sum_i \sum_j \sum_k (\rho g c) w p (T_{i,j,k}^{m+1} - T_{i,j,k}^m) \quad (3.13)$$

where  $C_{load\_p}$  is the ratio of load held in each zone over the calculation domain; the total of i, j, k is for the calculation domain and not for the whole furnace zone.

#### Heat absorbed by fixture:

Fixture is defined here as an element that directly holds or supports workpieces and moves forward with workpieces. Fixture doesn't include belt or conveyor. They always maintain the same temperature as the fastest heated workpieces.

$$Q_{fix\_p} = (w c)_{fix} (T_{fix}^{m+1} - T_{fix}^m) \quad (3.14)$$

Here it is assumed the fixture temperature is uniform in each zone and has the same temperature of the fastest heated workpiece.

#### Heat absorbed by moving belt or conveyor:

$$Q_{input\_p} = L_p (w c)_{belt} (T_{belt}^{m+1} - T_{belt}^m) \quad (3.15)$$

Where  $w$  is the weight of belt unit length.

It is assumed the belt temperature is uniform in each zone and has the same temperature of the fastest heated workpiece.

**Heat loss from furnace wall:**

$$Q_{loss\_p} = 2(L_p W_p + L_p H_p + H_p W_p) \frac{T_{fce\_p} - T_{room}}{t_1/k_1 + t_2/k_2 + 1/\alpha} \quad (3.16)$$

where  $T_g$  and  $T_a$  are the temperature of furnace gas inside and outside of furnace respectively;  $t_1$  and  $t_2$  are the thickness of first and second insulations;  $k_1$  and  $k_2$  are the heat conductivity of two insulations;  $\alpha$  is the thermal diffusivity from furnace outside to atmosphere.

**Heat absorption by furnace shell cooling water:**

$$Q_{shell\_cooling\_p} = (\rho g c)_{water} v \Delta t (T_{out} - T_{in}) \quad (3.17)$$

where  $v$  is the flow rate.

**Heat transfer between adjacent zones and heat loss from ends:**

$$Q_{zone\_p} = \text{wall height} * K \quad (3.18)$$

$K$ - constant. The heat transfer between heating zones can be neglected. While the heat transfer between hot zone and cold zone, between end zones and atmosphere cannot be neglected.

**Heat release by circulation fan:**

$$Q_{fan\_p} = HP_{fan} \left( \frac{520}{460 + T_{fce}} \right) \Delta t \quad (3.19)$$

where  $P_{fan}H$  is the power of the fan.

**Heat input by the furnace:**

$$Q_{fce\_p} = K_{AH\_p} \cdot q_{conn} \Delta t \quad (3.20)$$

**Net heat input:**

$$Q_{net\_p} = K_{PID\_p} K_{AH\_p} q_{conn\_p} \Delta t \quad (3.21)$$

where  $K_{PID\_p}$  is the constant for PID control; is the constant for combustion. For electric furnace  $K_{AH\_p}$  is 1.  $q_{conn\_p}$  is the heat connected input by dialog .  $K_{PID\_p}$  is calculated as follows

$$K_{PID\_p} = \frac{(T_{sp\_p}^m - T_{fce\_p}^m)}{P \cdot T_{span}} + D \frac{T_{fce\_p}^m - T_{fce\_R}^{m-1}}{\Delta t} + I \Sigma (T_{sp\_p}^m - T_{fce\_p}^m) \Delta t \quad (3.22)$$

### 3.3 Heat transfer model

The temperature history of the loaded furnace in the heat treating cycle is a hybrid convection/radiation heat transfer process. According to the heat transfer theory and energy balance equation, the heat exchange of loaded furnace can be mathematically presented in the following model:

$$q_{\_storage} = \sum_{i=1}^N \left( \rho_i \cdot cp_i \cdot V_i \cdot \frac{\partial T_i}{\partial \tau} \right) \quad (3.24)$$

where N is the quantity of accessories in the furnace. For convenience, we assume that all the accessories have the same Let time step be k and time calculation interval be  $\delta\tau$ . The equation can be rearranged in the time step (k+1) for the average furnace temperature.

$$T_{\_fce}^{k+1} = T_{\_fce}^+ + \frac{q_{\_storage}^k \delta\tau}{\sum_{i=1}^N k+1 \left( \rho_i \cdot cp_i \cdot V_i \cdot \frac{\partial T_i}{\partial \tau} \right)} \quad (3.25)$$

where  $q_{\_storage}$  is the average storage of heat flux in loaded furnace;  $\delta\tau$  is the time interval;  $\rho_i$ ,  $cp_i$ , and  $V_i$  are the density, specific heat, and the volume of accessory i in the furnace. These accessories include all the components involved in the heat treating process except for the workpieces. Eq. 3.25 can be used to calculate the furnace average temperature at time step (k+1). The equation is further grouped and rewritten as:

$$T_{\_fce}^{k+1} = T_{\_fce}^+ + \frac{Q_{\_storage}^k \delta\tau}{HC_{\_fce}} \quad (3.26)$$

where,  $Q_{\_storage}$  is the heat storage in heat-treating furnace;  $HC_{\_fce}$  is the heat capacity of furnace components; k is the time step; and  $\delta\tau$  is the time interval.



### 3.3.1 Factors that affect the furnace temperature calculation

The main factors affecting the furnace temperature are loads and heat storage. Loads include parts and all the furnace accessories, and heat storage is related to the furnace heat input, furnace control method, and furnace heat loss as shown in Fig. 3.5

### 3.3.2 Different loads considered for temperature calculation

In a loaded furnace, many components are involved in the heat treating cycle besides workpieces and all are referred as 'load'. These include furnace alloy, insulation wall, and heating elements as shown in Figure 3.3. Generally the loads other than workpieces are divided into three types:  $m$  furnace alloy including grate, firing-ring, U- tube, fixture, roller, fan and diffuser, etc;  $\hat{m}$  heating elements;  $m$  insulation.

### Effective heat capacity calculation of furnace components

$$HC_{fce} = HC_{alloy} + HC_{heater} + HC_{insulation} \quad (3.23)$$

where,  $HC_{alloy}$  is the furnace alloy heat capacity,

$HC_{heater}$  is heater heat capacity,

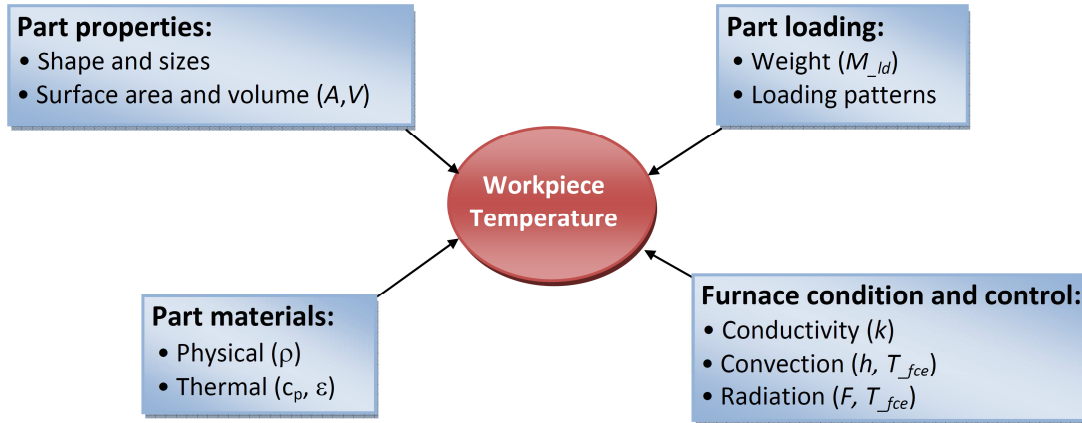
$HC_{insu}$  is furnace insulation heat capacity

### 3.3.3 Factors that affect the part temperature calculation

There are four main factors affecting part temperature in heat treatment, they are part properties, part loading, part materials, and furnace condition and control, as shown in Figure 3.3. The part temperature history in the heat treating furnace is a 3-D conduction heat transfer process with hybrid convection/radiation boundary conditions. It depends on the furnace temperature, working conditions, and part properties. Part load patterns and the thermal schedule design are the main tasks in the heat treatment process planning to guarantee the heat treatment quality. In order to simplify the temperature calculation, three basic assumptions are made here first:

- Lumped-mass problem, i.e., temperature in part is uniform;

- Air temperature in the furnace space is uniform; and
- Convection heat transfer on the part surface is uniform.



**Figure 3.3** - The factors affecting the workpiece temperature

In a heat treating process, parts are subjected to both convection and radiation heat transfer. Apply the energy balance equation to the part, then,

$$E_{\text{storage}} = E_{\text{convection}} + E_{\text{radiation}} \quad (3.27)$$

where,  $E_{\text{storage}}$  is the heat storage in the workpiece;  $E_{\text{convection}}$  and  $E_{\text{radiation}}$  are the heat obtained from convection and radiation heat transfer, respectively.

Let the volume and surface area of the part are  $V$  and  $A$ . The energy terms in Eq. 3.27 can be calculated using following equation:

(1) Convection at ambient temperature  $T_{fce}$ :

$$E_{\text{convection}} = h \cdot A \cdot (T_{fce} - T) \quad (3.28)$$

where  $h$  is the convection heat transfer coefficient,  $T$  is the temperature of workpiece,  $T_{fce}$  is furnace temperature.

(2) Radiation at heat source temperature  $T_{heater}$ :

$$E_{\text{radiation}} = \varepsilon \cdot \sigma \cdot F \cdot A \cdot (T_{fce}^4 - T^4) \quad (3.29)$$

where  $\varepsilon$  is emissivity,  $\sigma$  is Stefan Boltzmann constant,  $F$  is view factor between furnace wall and workpiece,  $T$  is the temperature of workpiece.

(3) Heat storage interior workpiece:

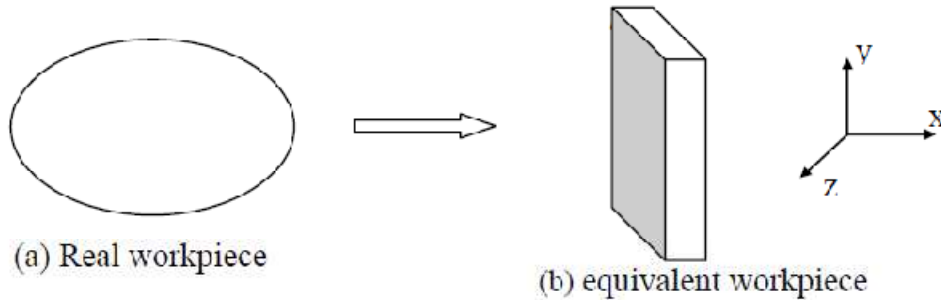
$$E_{storage} = \rho \cdot c_p \cdot V \frac{dT}{d\tau} \quad (3.30)$$

where  $\rho$  is the density of workpiece,  $c_p$  is the specific heat, and  $\tau$  is the time.

Combine Eqs. 3.28, 3.29 and 3.30 into Eq. 3.31, then

$$\rho \cdot c_p \cdot V \frac{dT}{d\tau} = h \cdot A (T_{fce} - T) + \varepsilon \cdot \sigma \cdot F \cdot A (T_{fce}^4 - T^4) \quad (3.31)$$

Since the part is taken as the lumped-mass body, we can imagine an equivalent workpiece or “visual workpiece” to represent the real workpiece. In this way the calculation can be further simplified.



**Figure 3.4 - The equivalent workpiece**

Let  $V = A \cdot t_{equ}$ , where  $t_{equ}$  is the equivalent thickness of the part. Apply finite difference method to the left-side of Eq. 3.31, then

$$\frac{\partial T}{\partial \tau} = \frac{T^{k+1} - T^k}{\delta \tau} + O(\delta \tau) \quad (3.32)$$

where  $k$  is the time step. By combining Eqs. 3.31 and 3.32, at time step  $k$ , the equation becomes,

$$T^{k+1} = T^k + \frac{\delta\tau}{\rho.c.t_{equ}} \left[ h.(T_{fce}^k - T^k) + \varepsilon.\sigma.F.((T_{fce}^k)^4 - (T^k)^4) \right] \quad (3.33)$$

Eq. 3.33 can be used to calculate the part temperature with uniform temperature distributions at any time in a heat treating cycle.

Above equations can be used to calculate the part temperature at arbitrary position in the furnace. Because there are different work environment at different positions in furnace space, the temperatures are different for different parts too. In practice, the temperature histories of all the parts have to be considered so as to get the good products.

The effect of work piece quantity and equivalent thickness

If lots of parts are treated in a heat treat cycle, we have to assure that all the parts are well heated during the process. It is not necessary to calculate the temperature-time profile for every part in furnace. Instead, the temperature-time profiles of some typical parts are considered in the furnace (such as the parts close to furnace wall and in the middle of furnace). The part load effect on the part temperature is mainly contributed from the radiation heat transfer and will be discussed in a later section.

The reason to calculate equivalent thickness is that sometime we need not only the surface temperature on the work piece, but also the core temperature. This is a simple method used to calculate the interior temperature of a part. There are several methods that can be used to calculate the equivalent thickness of a workpiece. The calculation methods will depend on the load conditions and calculation methods:

- The minimum dimension of heaviest cross section in work piece
  - The value of work piece volume divided by surface area:  $t_{eff} = V/A$
  - The value of 3 times of volume divided by surface area:  $t_{eff} = (3 \cdot V)/A$
  - The value of volume divided by exposition area to heater:  $t_{eff} = V/A$  exposition
- In our development of CHT, the first method is used as default value which can be changed through a user interface.

### **The effect of convection heat transfer**

In practice, the convection heat transfer around part surface is not uniform. This can be described using convection film coefficient  $h$ . Following is one of the calculation methods for the coefficient  $h$ :

$$h = (k \cdot Nu) / L^* \quad (3.34)$$

where  $Nu$  is Nusselt number, a dimensionless heat transfer coefficient, and can be calculated using an experimental equation[11]:

$$Nu = c \cdot Re^m \quad (3.35)$$

where  $Re$  is Reynolds number, a dimensionless group characterizing a viscous flow; the characteristic dimensions  $c$  and  $m$  are calculated from experimental values. Note that this equation is only used to gases medium.

$$Re = (V \cdot L^*) / \nu = (\rho \cdot V \cdot L^*) / \mu \quad (3.36)$$

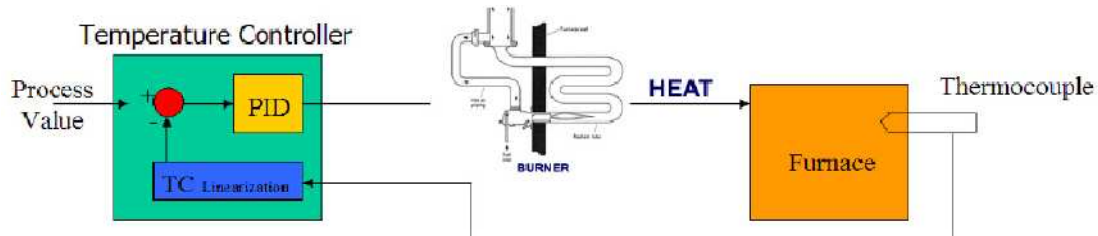
where  $L^*$  is a characteristic length of the part;  $k$  is the thermal conductivity;  $V$  is air velocity;  $\nu$  is the kinematic viscosity;  $\rho$  is density; and  $\mu$  is dynamic viscosity.

### **The effect of radiation heat transfer**

Because the parts are located in the different positions in the furnace, the heat they receive from the radiation transfer are different. This effect can be represented by the view factors. The value of view factor is affected mainly by the distance between furnace wall and the part, as well as the shadowing among work pieces. A CAD-based method of calculating the view factors is developed, the view factors can be specified based on the CAD-based calculation method.

### 3.4 Furnace temperature control model

The furnaces are controlled by temperature controllers. The temperature controllers get their inputs from a thermocouple located inside the furnace and send necessary control action to the burner to maintain the process set point.

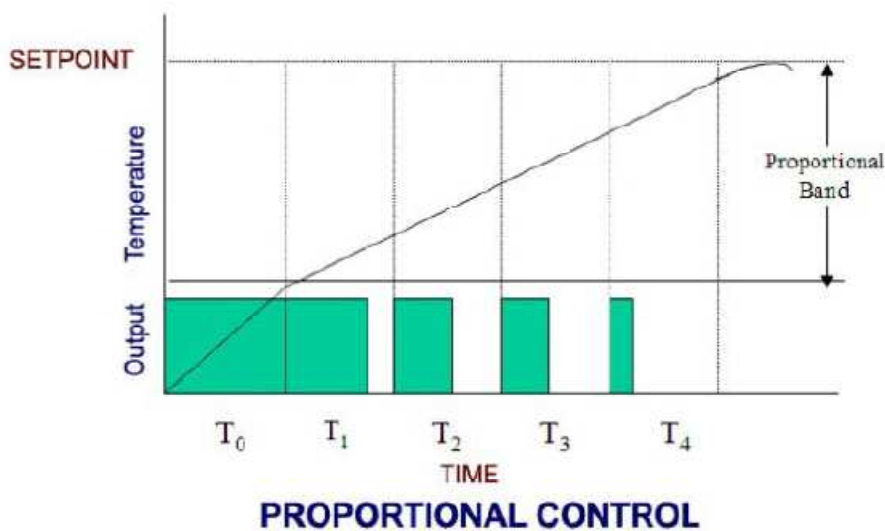
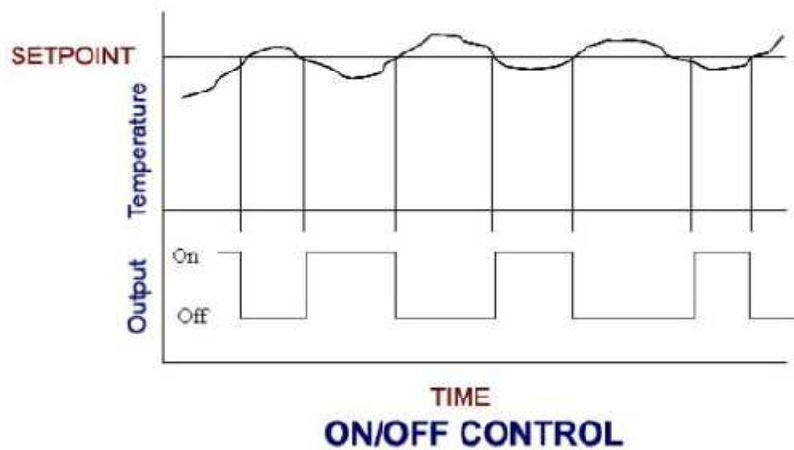


**Figure 3.5** - Schematic of the Temperature controller in a radiant tube type furnace.

#### 3.4.1 Commonly used schemes in heat treatment furnaces

The control action for the temperature controller can be either on/off or proportional. Process tolerances and the final device being controlled normally determine the type of control action.

On/off control is simple to understand. For example in a heat treat furnace during the heating process, if the measured process temperature is below the control set point, burners are continuously fired by the controller. If the measured value exceeds the control set point, the controller shuts the burners. Switching the heat on and off takes place at set point. This type of control causes the process value to oscillate around the control set point.



**Figure 3.6** - On/Off & Proportional type controllers commonly used in furnaces.

Proportional control (PID) is a more sophisticated control approach which results in tighter control around a setpoint and less process oscillation.

Proportional control consists of 3 basic control functions:

1. Proportional band
2. Reset, or Integral
3. Rate, or Derivative

Proportional band is the process range over which proportioning control action takes place. In a heating situation, if the process temperature is below the proportional band,

burners are continuously fired by the controller. If the process value is above the proportional band, the burners are shut. Within the proportional area, as the process temperature increases the amount of heat being called for decreases proportionately. (where T1, T2, T3... are the proportionally decreasing time values)

To determine the proper proportional band setting, the time required to approach setpoint must be balanced with the processes' ability to withstand overshoot. If proportional band is too narrow, the heat input will not be cut back soon enough and the process will overshoot. A wide proportional band begins cutting back the heat input sooner. A narrow proportional band (means heat is on longer) will approach setpoint quicker than a wide proportional band.

Reset (Integral) shifts the proportional band in relation to the desired setpoint. Reset action is used to compensate for sustained process offset from the control setpoint.

Rate (Derivative) is used to compensate for initial overshoot and sudden process disturbances. Rate will temporarily compress the proportional band around setpoint to bring the process under control.

### **3.4.2 Controller tuning**

It is necessary to tune a controller to a particular process. This will enable the controller to maintain tight control of the process. This will remain so even if process variables (ambient temperature, load size, hearth/gasket condition, etc.) change over time.

Properly tuning a controller to a process is an absolute necessity to ensure tight control. Manually tuning a controller is a time consuming and tedious exercise. There are several features available in today's controllers which facilitate tuning. Autotune capability now allows a controller to tune itself to a process. Autotune will introduce a minor process disturbance and this enables the controller to determine how the process should react to the change and the amount of time required to recover. Based on these parameters the controller determines the necessary constants.

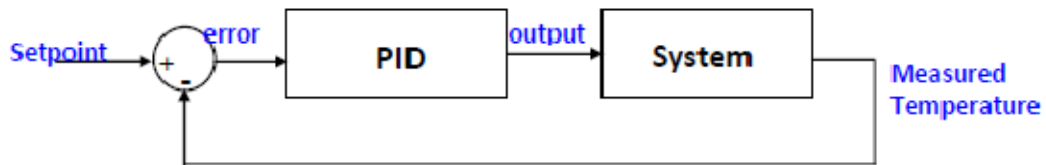


Another method of tuning the modern controllers is by using the Adaptive tuning. Adaptive tuning is implemented by the controller and results in minor proportional band, reset, and rate changes. Adaptive tune does not introduce process disturbances.

Fuzzy logic is the newest function incorporated into controllers. It is supposed to enable a controller to learn a process, and subsequently react quicker to changes. Currently the CHT model can accept the PID based controller values. The controllers with adaptive and fuzzy logic based schemes need to be translated to PID based values.

### 3.4.3 CHT furnace - PID control model

The typical temperature control method in the furnace is PID controller. When the measured temperature is different from the set point temperature, the heating or cooling input is controlled to minimize the error. It is a typical feedback control system as shown in Figure 3.7.



**Figure 3.7** - Control feedback loop of PID control

Generally PID method uses following equation to control the loop:

$$u = P \cdot \left[ (T_s - T_0) + D \cdot \frac{d}{dt} (T_s - T_0) + I \cdot \int (T_s - T_0) dt \right] \quad (3.37)$$

where  $T_s$  is the set point temperature,  $T_0$  is the furnace temperature, the error value  $e = (T_s - T_0)$ ; P, D, and I are known as proportional gain, damping, and integral gain, respectively.

In a PID control process, one of the most important things is to set the P, D, and I. Tuning these constants so that the weighted sum of the proportional, integral, and derivative terms produces a controller output that steadily drives the process variable in the direction required to eliminate the error. There are several methods that can be used to determine the P, D, and I value. One of them is Ziegler and Nichols approach, which is a practical method of estimating the values of K, T, and d experimentally. Where K is the process gain used to represent the magnitude of the controller's effect on the process variable, T is the process time constant used to represent the severity of the process lag, and d is the deadtime used to represent another kind of delay present in many processes. With the controller in manual mode (no feedback), a step change is included in the controller output and the process reaction is analyzed. The process gain P can be approximated by dividing the net change of the process variable by the size of the step change generated by the controller. The dead time is estimated from the interval between the controller step change and the beginning of a line drawn tangent to the reaction curve at its steepest point. They are also used the inverse slope of that line to estimate the time constant T.

$$\left. \begin{aligned} P &= \frac{1.2.T}{K.d} \\ I &= \frac{0.6.T}{K.d^2} \\ D &= \frac{0.6.T}{K} \end{aligned} \right\} \quad (3.38)$$

Sometimes, when the sensor measuring the furnace temperature is susceptible to other electrical interference, derivative action can cause the heater power to fluctuate wildly. In this case  $D = 0$ , and a PI controller is often used instead of PID controller. The typical application of PD control in furnace is to control heat/cool gases input. The adjustment coefficient of heat input, Htg, is calculated using following equation:

$$Htg = \frac{PG}{span} (T_{-sp} - T_{-fce}) + \frac{PG.IG}{Span} \int_0^{\tau} (T_{-sp} - T_{-fce}) \quad (3.39)$$

where the proportional gain  $PG=10$  and the integral gain  $IG=0.05$ .

### **3.5 Summary**

The CHT furnace model is a comprehensive model with a capability to model several different types of furnaces and control schemes. Currently there are several proprietary models used internally by the industry that is not publicly available. The CHT model is the most comprehensive model currently available to the industry and is in use at several CHT member companies since 2002. The model used in the CHT software system and has been validated with several case studies.

The experiments conducted using the CHT software are grouped by Furnace type and the results are analyzed. The CHT-c/f calculated results are compared to the measured thermocouple results. The comparison between the results are performed by focusing on the following areas / issues,

- Heat up rate accuracy
- Time taken to reach furnace set point (comparison)
- Accuracy of soak time and temperature
- Abnormal peaks - gradients

Each area with high error percentages was analyzed to determine the cause of the problem. Some minor problems were attributed to software bugs which were fixed later. The major problems were studied in detail and expert opinion from the shop floor was requested to further understand the problem. A detailed list of problems in the current model due to furnace issues like gradients, furnace aging, and the model constraints are documented. The results presented in this chapter as based on the observations and conclusions based on the experimental results as documented further.

#### **4.1 Furnace model study**

To breakdown the analysis task, the model was studied from three practical perspectives,

1. Structural model
2. Control schemes model
3. Process related parameters

### **4.1.1 Structural model**

The furnace was studied from a structure stand point and several factors were classified and important to the accuracy of the model. The several problems and their effects are listed below.

#### **Universal furnace**

The current model is universal for all furnaces. Due to this issue its unable to calculate the heat losses that are more specific to certain kinds of furnace. The effect of having a universal furnace is in the improvement in the accuracy certain heat loses and heat storage in the furnace ( $Q_{fce}$ ) if we have more specific furnace categories. (eg: Vacuum, Box, Pit, etc.,)

#### **Burner locations**

Thermal gradient in the furnace due to location of the burners and their BTU's. There is a thermal gradient inside the furnace and the BTU is not distributed uniformly inside. Current model assumes uniform furnace temp. And Accuracy issues especially in Continuous furnaces.

#### **Atmosphere flow**

The effect of atmosphere flow and calculating a constant to adjust the heating parameters due to the heat losses. These result in accuracy issues. Case studies done for validation in the atmosphere furnaces show the inconsistency especially during heat up.

#### **Incomplete accessory data**

Make a generic list of accessories for each kind of furnace. Improves the model accuracy by considering all the furnace elements.

### **4.1.2 Control model**

Similar to the structural model all the elements that contribute to the furnace control were studied separately and their effects are listed below.

## **Furnace controller**

In the current model there is no option to specify the exact control schemes used in the furnace. This results in approximation of the control scheme that is deployed in the shop floor.

## **Multiple controllers**

There is no option to specify multiple controller parameters for different zones. Also the controllers are tuned differently for different zones based on the process parameters especially in the continuous furnaces. These result in inaccurate thermal profile calculation.

## **Control thermocouple**

There is often a thermal gradient inside a furnace and one of the reasons is due to the location of the control thermocouple. Currently the model assumes a uniform temperature distribution. The control thermocouple location information helps to calculate the gradient present inside the furnace.

### **4.1.3 Process parameters**

Several processes require the furnace to be controlled differently. The main differences are in the atmosphere control and the temperature control. The experiments were conducted for the current list of processes,

1. Annealing
2. Tempering
3. Carburizing
4. Brazing

## **4.2 Problem identification in the current CHT furnace model**

A detailed study of the experimental analysis based on Furnace classification, Control schemes and Process related parameters revealed the following limitations or

issues in the current CHT model. Several of these also have an effect on the model accuracy.

### **1. Universal furnace model**

The current model is based on an universal model for all furnaces. Hence it cannot accurately calculate the heat losses that are more specific to certain kinds of furnaces. (eg: Vacuum, Box, Pit, etc.,)

### **2. Burner locations**

Current model assumes uniform furnace temperature, often there is a thermal gradient in the furnace due to location of the burners and their capacities.

### **3. Atmosphere flow**

Case studies done for validation in the atmosphere furnaces show the inconsistency especially during heat up. The effect of atmosphere flow and the heat losses and heat transfer affects the accuracy of the model.

### **4. Furnace accessories**

Furnace accessories like baskets, fixtures, etc, also consume heat inside furnace along with the load. The current model uses a generic fixture approximation.

### **5. Door operations**

The current furnace model does not take into effect the heat loss arising due to the door operations during charging and discharging the parts from the furnace. From the experimental analysis this was not an issue in Batch furnaces but it had an impact on the continuous furnaces.

### **6. Furnace controller**

Inability to translate the control schemes used in the furnace to the PID based control in the furnace model.

## **7. Multiple furnace controllers**

The furnaces often use multiple controllers for different zones. The controllers are tuned differently for different zones based on the process parameters, especially in the continuous furnaces. Currently CHT model uses a universal controller.

## **8. Control thermocouple location**

It was found a thermal gradient inside the furnace may be present due to the location of the control thermocouple.

## **9. Process data**

Several processes require operating the furnaces differently. (For example, in the carburizing furnace, the enriching gas is added to the furnace after the load reaches the temperature. The ability to specify in the CHT model the amount of gas added in the cycle improves the calculation of heat loss, which is currently not possible)

## **10. Proprietary furnace control schemes**

The furnace and controller manufacturers use several proprietary furnace control techniques. Its difficult to model these control schemes. (for example - its difficult to determine the PID constants (for CHT model) from a controller tuned with an adaptive tuning algorithm)

## **11. Furnace deterioration (wear/tear)**

The furnace refractory and burners deteriorate over time, increasing heat losses and reducing heat available respectively.

## **12. Faulty or incorrectly tuned burners**

The burners need to be tuned properly for complete combustion. An incorrectly tuned burner or a faulty burner does not produce the specified heat.



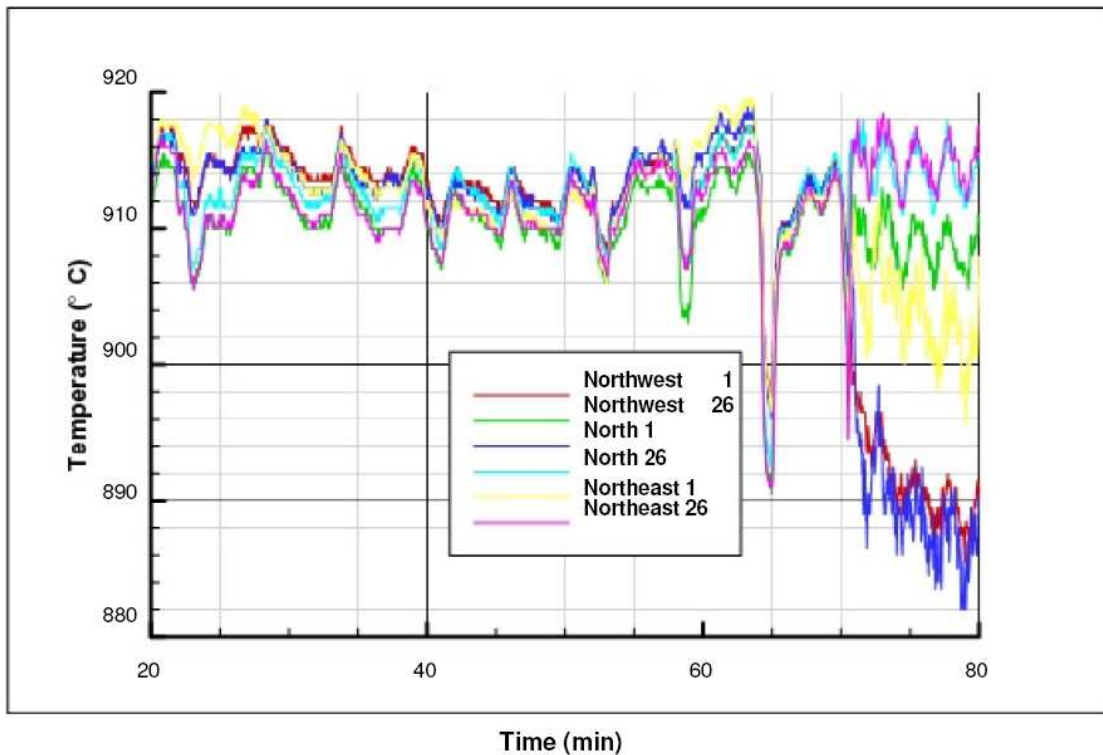
### **4.3 Summary & conclusions**

After analyzing all the list of limitations and problems in the current CHT furnace model heat loss due to door operations was determined to have significant effect on the furnace model accuracy.

The heat loss in the furnace due to door operation is a problem more significant in continuous furnaces than batch furnaces. With several experimental data and modeling we can develop new model to incorporate in the CHT model to account for this loss. The thermal gradients present inside the furnace is a complex phenomenon, it is caused due to several factors like burner and control thermocouple location, the furnace construction, etc., and it is also unique to every furnace, so more detailed study is required to understand and model this phenomenon. Furnace wear phenomenon can be modeled by conducting calibration experiments with virtual load and the parameters reverse calculated. These are the development proposed for the improvement of the CHT furnace model.

**5.1 Introduction**

The Furnace Model Analysis study gave an insight on the current CHT Furnace model’s shortcomings and opportunities to improve the overall accuracy. From one of the experimental results on a Continuous Pusher Furnace (as seen in Fig. 5-1a) we can see a significant thermal gradient present inside the furnace in the holding chamber and also there was a wave due to the heat loss from the door openings and the controller action. This problem is specific to this type of furnace and more due to the design and arrangement of the burners.



**Figure 5.1a** - The thermal gradients inside a Continuous Pusher Furnace, experimental data from continuous datapak with 6 thermocouples.

Based on the furnace model analysis presented the key focus was narrowed down to heat loss due to furnace charge / discharge door operations.

The new model is represented as follows by addition of 1 new term to the original equation,

$$T_{fce}^{k+1} = T_{fce}^k + \Delta T_{fce\_door}^k + \Delta T_{fce\_gradient}^k(x, y, z) + \Delta T_{fce\_virtual}^k \quad (5.1)$$

$T_{fce}^{k+1}$  - Furnace temperature (at time step, k)

$T_{fce\_door}^k$  - Furnace temperature variation due to door operations

$T_{fce\_gradient}^k(x, y, z)$  - Temperature gradient inside furnace in 3D space

$T_{fce\_virtual}^k$  - Furnace calibration using virtual load

Detailed explanation of the term, how it is calculated and used in the model are described in the following chapters. Experimental case studies are also conducted to verify the results.

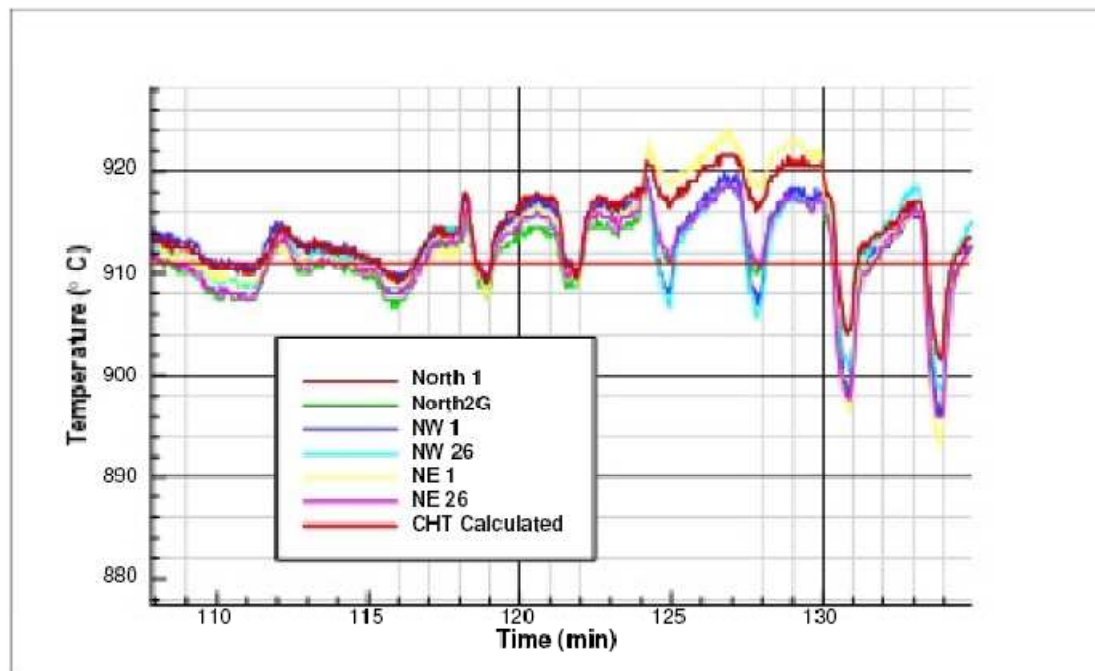
## 5.2 The Door Open model ( $T_{fce\_door}^k$ )

The CHT model does not calculate the heat loss and the heat exchange between zones that occur as a result of the door operation. Currently the furnace temperature is not calculated in the continuous furnace model based on the PID control. The calculated furnace temperature does not reflect the variation observed in the experiments. This chapter discusses addition of a heat term to compensate for the heat loss arising out of door operations.

### 5.2.1 Introduction

A series of experiments were conducted at the plant facility to evaluate the accuracy of the continuous furnace model under different conditions. The experiments were conducted on a brand new furnace undergoing production trials. This helped us eliminate some of the guess work out of calculation especially the heat loss factor due

to the physical wear and tear of the furnace. After conducting the experiments a significant variation between furnace set-point temperature and the measured work piece temperature (around 25°C) was noticed. There also existed a uniform pattern to the thermal profiles in all the experiments. This pattern matched with that of the door open sequence. This thermal pattern is shown in the Fig.5.1b.



**Figure 5.1b** - The thermal profile of the CHT calculated and measured work piece temperature at 6 different locations in a Continuous Furnace.

The current furnace model (CHT model) was developed based on the batch furnace model and the main assumptions in the model are,

- (i) The furnace temperature does not change with varying load conditions. It always remains same. (So the heat balance is not calculated and PID control is not considered either)
- (ii) The work piece movement is considered linear. (either step movement or continuous)

- (iii) The work piece is fixed and the furnace is moving. So the thermal schedule is a function of the movement speed. The furnace temperature is the same as thermal schedule.
- (iv) The heat transfer at the calculated domain boundary to other loads is zero.

With the work piece as a reference, the furnace temperature involved in the calculation changes with the work piece row number and time, the temperature is calculated for different zones. The furnace temperature distribution is a function of furnace zone and corresponding transition zone. It is depicted as follows:

$$T_{fue}(d) = \begin{cases} T_{zonej} + \frac{T_{zone(j+1)} - T_{zonej}}{L_j + L_{j+1}} (d - (\sum_{i=0}^j L_i - L_j)) & \sum_{i=0}^j L_i - L_j \leq d \leq \sum_{i=0}^j L_i + L_{j+1} \\ T_{zonej} & \sum_{i=0}^{j-1} L_i + L_j < d < \sum_{i=0}^j L_i - L_j \end{cases}$$

Since the temperature variations observed during the experiments were significant from a heat treatment processes stand point, it was decided to integrate new terms to the current Continuous Furnace model to improve the furnace temperature accuracy to reflect the real world conditions.

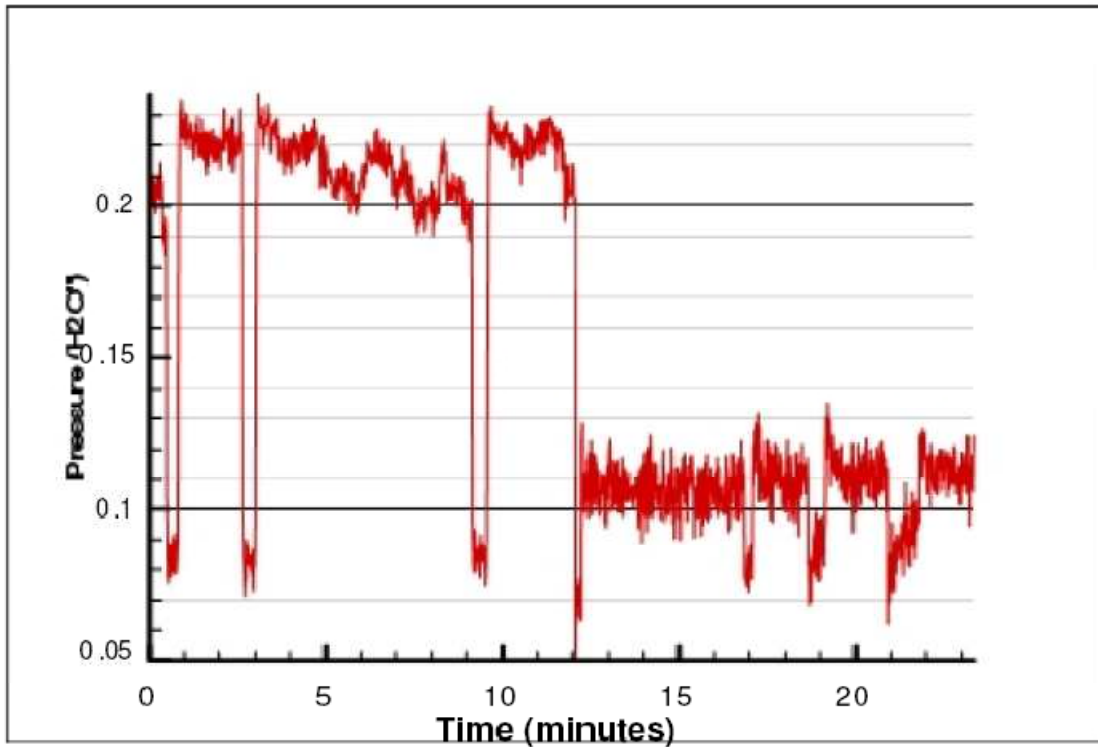
There are two modes of heat loss arising due to the door operation. A radiation heat loss and heat loss due to the exchange of the furnace gas between zones and to the atmosphere in the final zone. There are several doors in the furnace between zones. the door open sequence can be simulated starting from a fully loaded furnace. The door 5 is opened through a slot door for quenching, during this operation there is a radiation heat loss and also heat loss due to the loss of furnace atmosphere. Once the door 5 is closed the door 4 opens and parts are pushed in the final zone. During this operation there is a heat exchange through radiation depending upon the zone temperatures and normally there is not a significant amount of atmosphere exchange. (Assumed based data on the pressure variation during the door operation is presented later). The same sequence of operations follow during the operation of doors 3 and 2. When the door 1 opens a new cold part is loaded in the furnace. We do not model the first few zones, as there is a significant cold mass entering the furnace. There is no

temperature swings in the first few zones and the burners are firing at the maximum rate to achieve the set-point temperature.

The atmosphere exchange and heat loss in the final zone is complex. When the slot door opens, due to the pressure differential the furnace hot atmosphere escapes the furnace and at the same time there is cold air entering the furnace due to the vacuum created inside the furnace. This happens due to a drop in the furnace atmosphere volume because of the heat loss. It's difficult to calculate the exact volume of atmosphere lost and air added. Based on experimental data presented from a furnace manufacturer the velocity of hot air leaving the furnace is around 500-600 ft/min and usually this takes place in the top 1/3 space of the slot door. And the cold air velocity entering the furnace is around 100-200 ft/min.

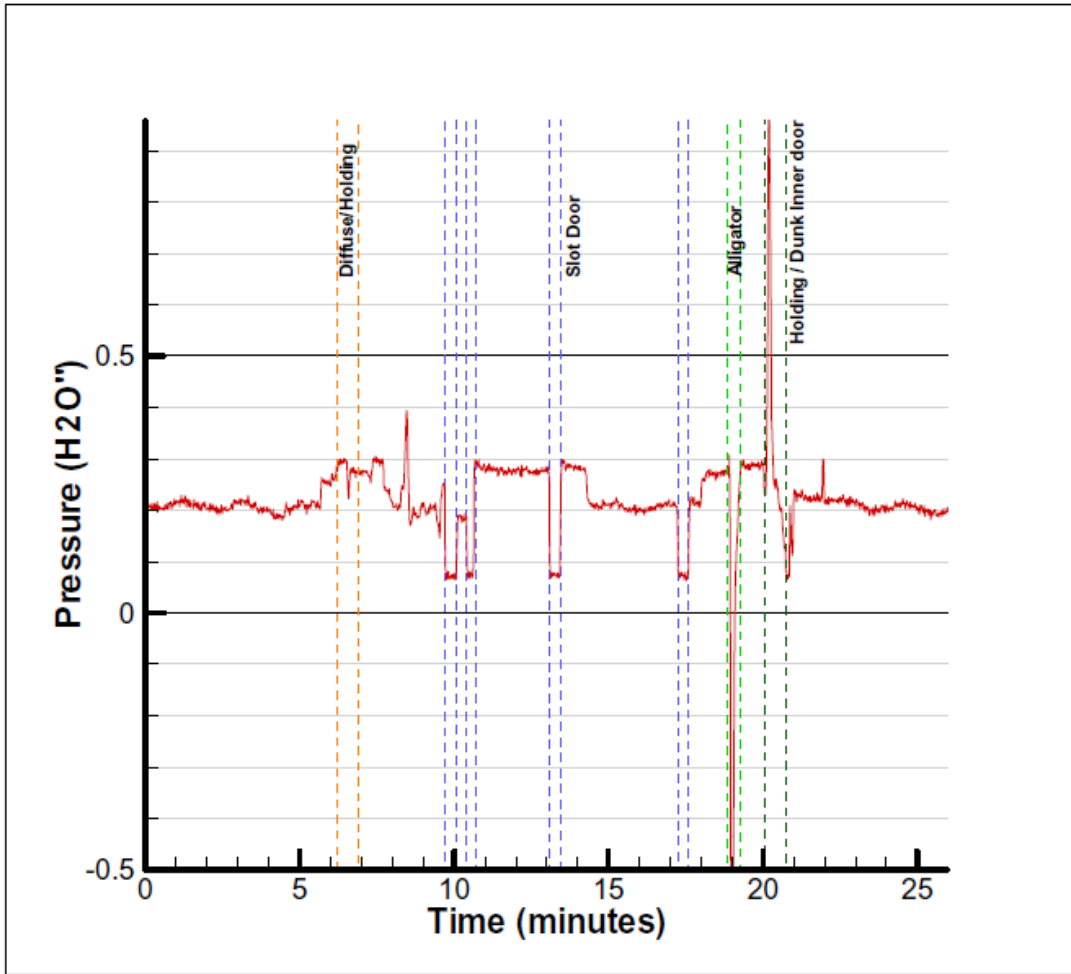
### **5.2.2 Experiments on pressure differences between zones & during door operations**

Further experiments were conducted to understand the gas exchange between the different zones in the furnace and to the atmosphere during the door operations. A series of experiments were conducted to study the pressure in the different zones in the furnace and the changes in pressure during the door operation.



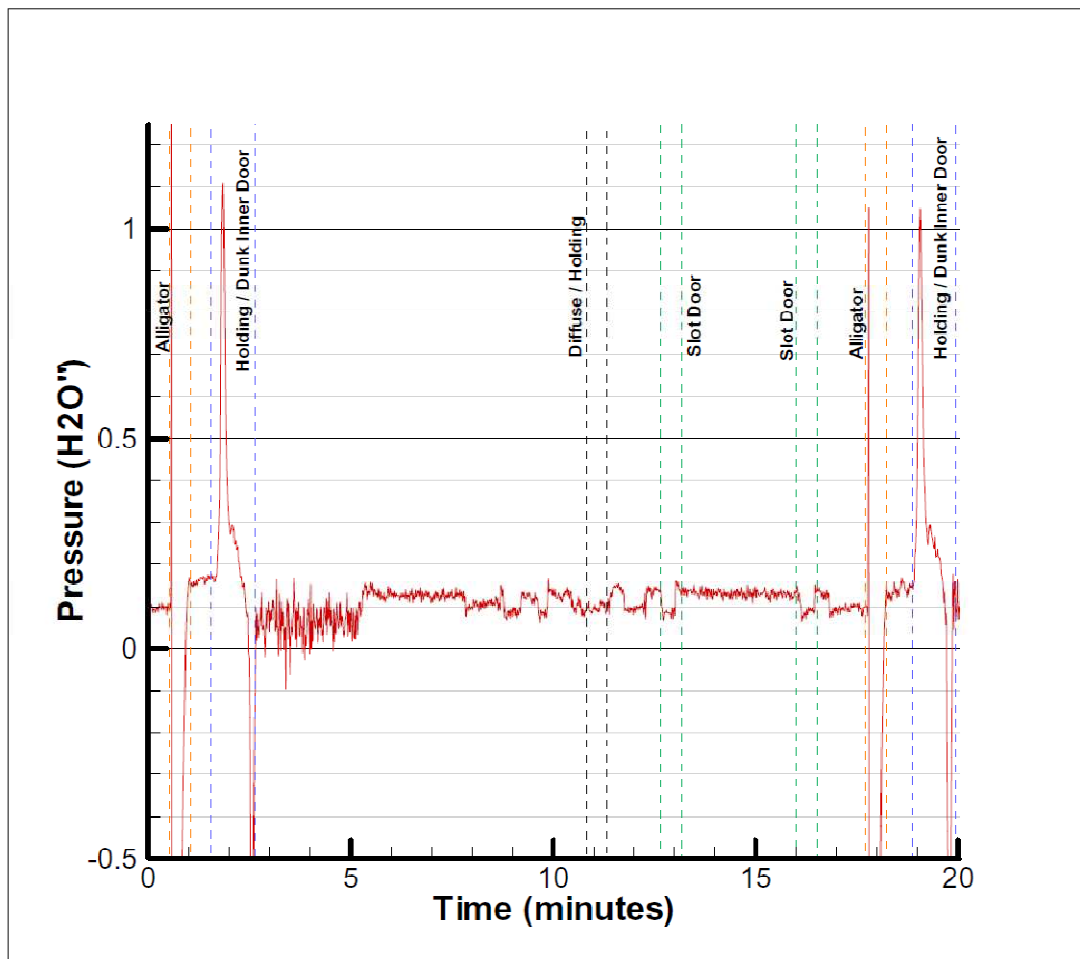
**Figure 5.2** - The pressure in two different final zones in a Continuous Pusher Furnace

Figure 5.2 shows the plot of pressure in Holding Chamber and Dunk Quench Chamber in inches of water (27.7 inches of Water = 1 PSI at 62° F). The pressure inside the furnace is slightly above the atmospheric pressure. Also the pressure in the holding chamber is maintained above the dunk quench chamber to prevent the gas from entering the holding chamber. This is done to prevent decarburization in the holding chamber.



**Figure 5.3(a)** - The pressure variations as a function of different door operations events. Holding Chamber





**Figure 5.3 (b)** - The pressure variations as a function of different door operations events. Quench Chamber

As observed in Fig. 5-3(a) the pressure variations in the different zones are plotted as a function of the different door operation events. One of the observations is that the door openings in a zone had an effect on the pressure on several different zones. It had a clear influence on the pressures in the adjacent zones and this implies that the intermediate zone doors are not pressure tight and hence there is exchange of gases that takes place during the door openings.

The negative pressure formed after the door operation is created due to the reduction in volume of gas. When the door opens a significant amount of air enters the furnace and creates

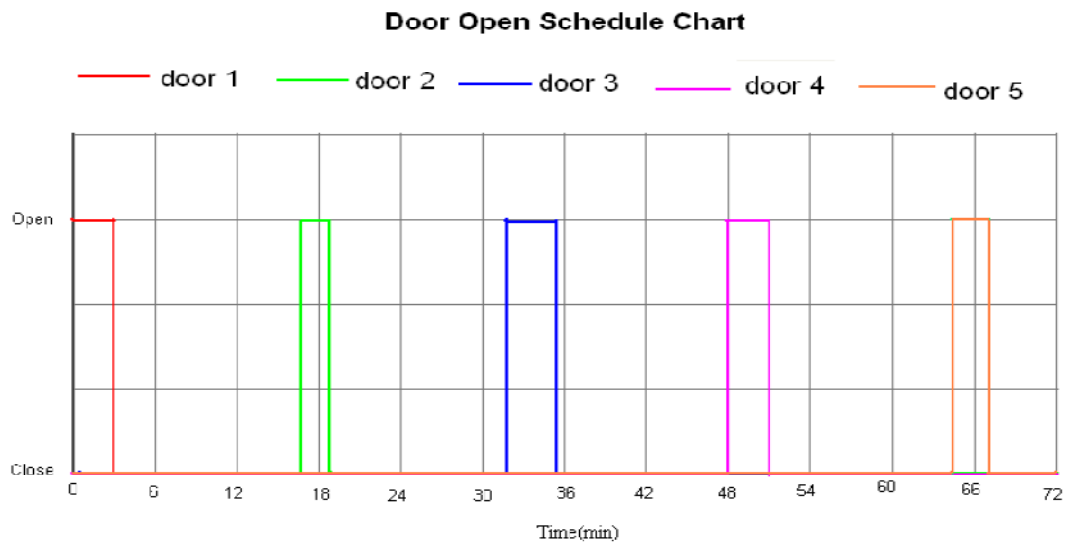
combustion of the endothermic gas present in the zone. When the door closes, pressure spikes due to the expansion of the gas due to higher temperature resulting from the combustion. And the combustion stops once all the oxygen is consumed from the air and this result in a significant reduction in the temperature and volume causing the pressure to go in the negative.

Based on the experimental data on temperature and pressure a new term was added to the current Continuous furnace model to account for the heat loss.

### 5.2.3 Modified model to include door open term

$$q_{storage} = q_{ht} - q_{loss} - q_{id} - q_{cl} + q_{fan} - q_{dopn} \quad (5.3)$$

where,  $q_{dopn}$  is the heat loss caused by radiation and mass loss during doors operation. ,  $q_{dopn}$  is also a function of time calculated from the door open schedule.



**Figure 5.4** - The door open schedule based on the furnace layout represented in the time domain

An assumption was made for creating the door open schedule. The door is either open or closed so the intermediate positions are not considered in the schedule as shown in Fig.5-4.

The  $q_{\text{dopn}}$  is calculated based on the following equations,

$$q_{\text{dopn}} = \begin{cases} q_{\text{dopn\_rad}} + q_{\text{dopn\_air\_exchange}}, & \text{while the last door} \\ q_{\text{dopn\_rad}}, & \text{while not the last door} \end{cases} \quad (5.4)$$

$$q_{\text{dopn\_rad}} = \eta \cdot \varepsilon \cdot \sigma \cdot A_{\text{open}}(\tau) \cdot (T_{\text{fce}}^4 - T_{\text{door\_outside}}^4) \quad (5.5)$$

$$A_{\text{open}}(\tau) = \begin{cases} A_{\text{door,m}}, & \text{while door open} \\ 0, & \text{while door close} \end{cases} \quad (5.6)$$

As shown in equation (5.4) another assumption was made based on the experiments that there is not significant loss of heat in the intermediate zones due to the air exchange.  $q_{\text{dopn\_air\_exchange}}$  is calculated only for the last zone.

$$q_{\text{dopn\_air\_exchange}} = c \cdot \sqrt{\frac{\pi^2 d^5}{16 \lambda R T_{\text{fce}}}} \cdot (p_{\text{fce}}^2 - p_{\text{door\_outside}}^2) (T_{\text{fce}} - T_{\text{door\_outside}}) \quad (5.7)$$

$$= c \cdot k_d \cdot (T_{\text{fce}} - T_{\text{door\_outside}})$$

where,

$d$  is the equivalent diameter of the door,

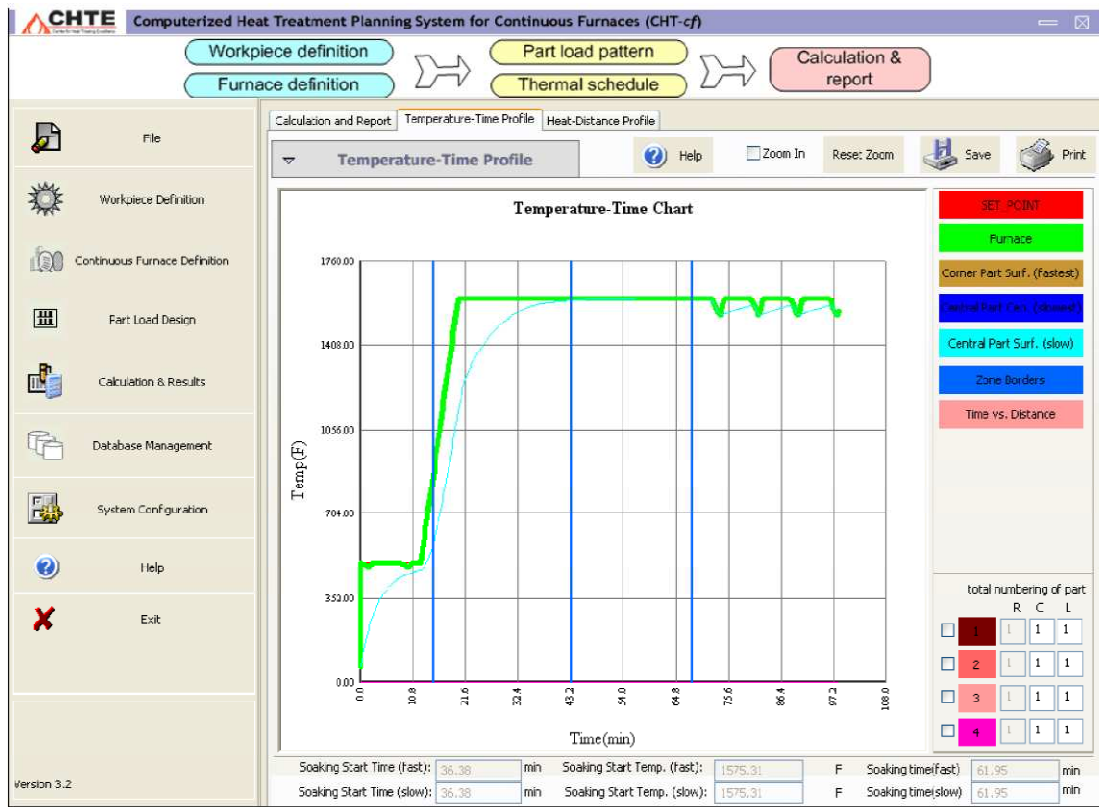
$\lambda$  is the coefficient of heat conductivity,

$l$  is the thickness of the door,  $R$  is the gas constant,

$p_{\text{fce}}$  is the pressure in the door,

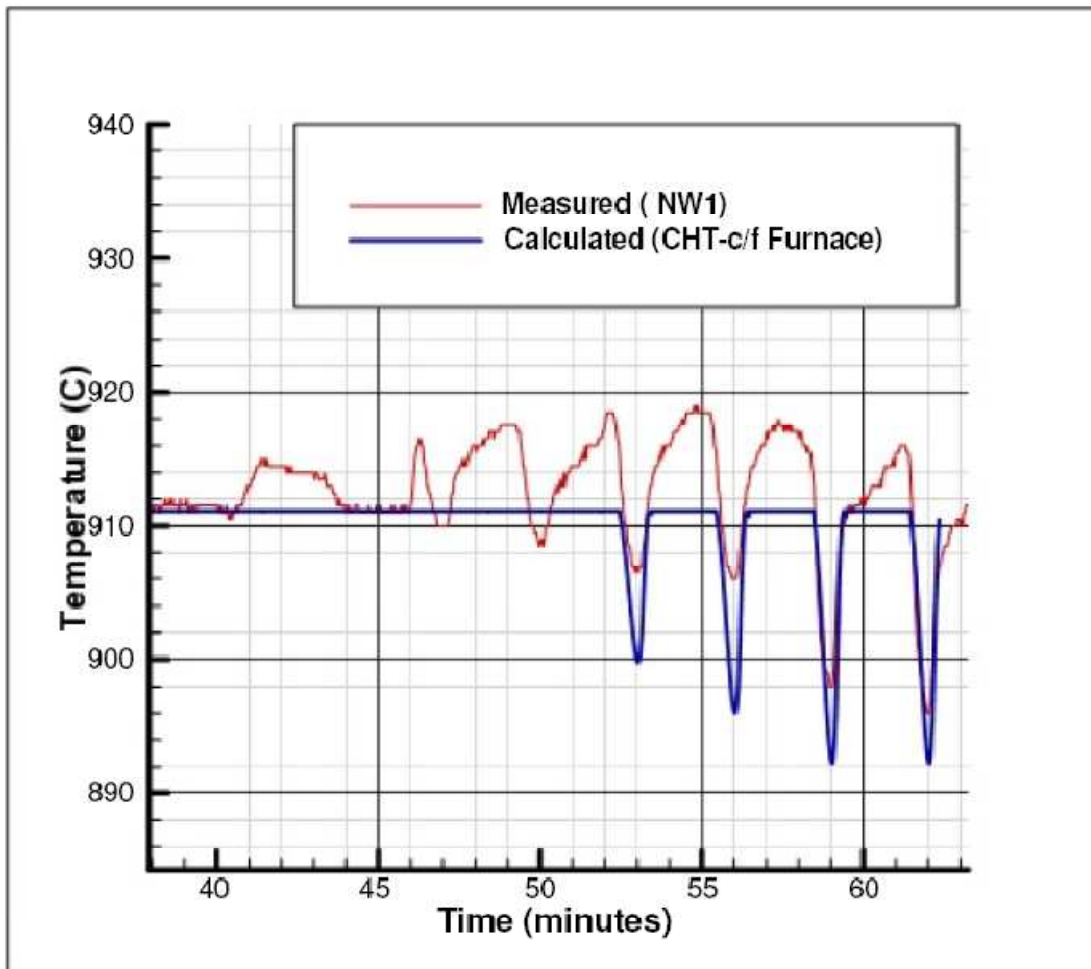
$p_{\text{door\_outside}}$  the pressure outside the door, and

$kd$  is the empirical coefficient of heat convection (for the current furnace its 3.5 m/s based on the pressure experiments).



**Figure 5.5** - The screen shot of the furnace thermal profile computed by CHT-c/f software using the improved furnace model

As observed in Fig. 5-5 the new thermal profile computed using the improved furnace model reflects the furnace temperature drops due to the door operation in the first and the final zones. This plot also shows the effect on the part temperature due to the variation in the furnace temperature. Another experiment was conducted to verify the improved furnace model.



**Figure 5.6** - The comparison of the furnace thermal profile computed using improved furnace model and measurement results.

As seen from the above Fig. 5-6 as well as from Fig. 5-5 the computed results now take into account the heat loss due to the furnace door operations. Fig. 5-6 also illustrates that the calculated furnace thermal profile is in good agreement with the measured results. This helps in accurate calculation of the part temperature profile especially in the last zones where the temperature of the part is critical in carburizing operations.

#### **5.2.4 Conclusions**

The new improved model was verified with experiments to take into consideration the heat loss involved with the door operations. The same modeling method can be used to determine the heat loss involved with other type of continuous furnaces, but in this study the model was verified only with the Pusher type continuous furnaces. Some of the problems with this new door model are: to accurately determine the heat loss due to door opening, and to differentiate the peaks arising due to the PID controller. The key to accurately determine the door opening peaks is to understand and filter the false peaks arising out of the controller activity.

- The Furnace Model Analysis study gave an insight on the current CHT Furnace model's shortcomings and opportunities to improve the overall accuracy. From one of the experimental results on a Continuous Pusher Furnace (as seen in Fig. 5-1a) we can see a significant thermal gradient present inside the furnace in the holding chamber and also there was a wave due to the heat loss from the door openings and the controller action. This problem is specific to this type of furnace and more due to the design and arrangement of the burners.
- After conducting the experiments a significant variation between furnace set-point temperature and the measured work piece temperature (around 25°C) was noticed.
- The heat loss in the furnace due to door operation is a problem more significant in continuous furnaces than batch furnaces. With several experimental data and modeling we can develop new model to incorporate in the CHT model to account for this loss. These are the development proposed for the improvement of the CHT furnace model.
- As observed in Fig. 5.3(a,b) the pressure variations in the different zones are plotted as a function of the different door operation events. One of the observations is that the door openings in a zone had an effect on the pressure on several different zones. It had a clear influence on the pressures in the adjacent zones and this implies that the intermediate zone doors are not pressure tight and hence there is exchange of gases that takes place during the door openings.
- The negative pressure formed after the door operation is created due to the reduction in volume of gas. When the door opens a significant amount of air enters the furnace and creates combustion of the endothermic gas present in the zone. When the door closes, pressure spikes due to the expansion of the gas due to higher temperature resulting from the combustion. And the combustion stops once all the oxygen is consumed from the air and this result in a significant reduction in the temperature and volume causing the pressure to go in the negative.
- Based on the experimental data on temperature and pressure a new term was added to the current Continuous furnace model to account for the heat loss.

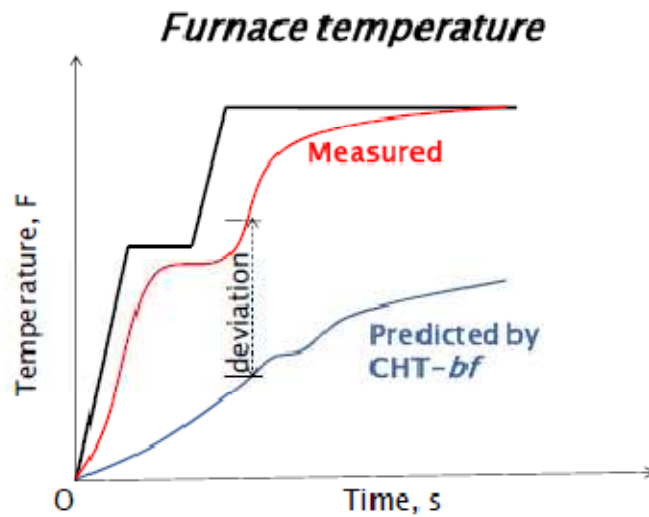
- The new improved model was verified with experiments to take into consideration the heat loss involved with the door operations. The same modeling method can be used to determine the heat loss involved with other type of continuous furnaces, but in this study the model was verified only with the Pusher type continuous furnaces. Some of the problems with this new door model are: to accurately determine the heat loss due to door opening, and to differentiate the peaks arising due to the PID controller. The key to accurately determine the door opening peaks is to understand and filter the false peaks arising out of the controller activity.

The main issue of current CHT technology has been identified as,

- Universal furnace model is used for all furnaces even though the individual furnaces are designed differently;
- Even for the same type of furnaces, the performance may vary under different production environments and at different life time of the furnace;
- Since the furnace model used is an approximation, the user can not modify the model accurately to achieve the desired results; and
- There is no method to evaluate the different models to help diagnose the issue, and find a solution.

The heat items are empirical equations gained from experience and essential to the furnace temperature prediction. However furnaces are of different types, operation strategies, working conditions etc.





**Figure 6.1** - Error of predicted furnace temperature

Therefore the predicted furnace temperature deviates from the actual measurements in some cases, as shown in Fig. 6.1. This means the calculated heat distribution inside the furnace is not accurate.

Developing a breakthrough technology through adaptive modeling to improve the simulation accuracy is necessary to commercialize the CHT technology, and thus promote the market growth for the CHT technology and broaden the utilization of the CHT software tools.

For CHT technologies, CHT- c/f, an accurate set of furnace rules and knowledge are essential to simulate and optimize the heat treatment processes. This knowledge is hard to discover from the limited number of furnace studies, and production data that are available. Since this data will change from furnace to furnace, load to load, a more flexible furnace model which is adaptable to these changes is desired.

The different models used in the CHT software, Energy balance model, Heat transfer model and Control model were studied and shown how they contribute to accuracy of the furnace and part temperature profiles. Several experiments were conducted to compare and analyze the CHT predictions with the measured results in the shop floor. Based on experimental analysis several problems were identified. Some of the problems were solved using knowledge from experimental data. The continuous furnace model was modified to account for the heat loss arising from the door operations. These specific problems like thermal gradients are prevalent only in furnaces with certain burner layouts. Taking the burner location and design into account two methods for predicting the thermal gradients inside the furnace are proposed.

**Limitations**

Some of the limitations of the proposed work in this research are the availability of experimental data. The thermal gradient model is based on experimental data and is not possible to represent the gradients, unless a few experiments are conducted at several locations in the furnace. In the continuous furnaces it is difficult and expensive to conduct such experiments. A datapack device that has a thermally insulated data recorder to withstand high temperatures over the duration of the process (typically several hours) is required to measure the temperature inside the furnace. Also the specifications of the datapack device itself become constraints while conducting experiments.

The time allowed for the datapack to stay inside the furnace at a specified temperature has to be considered while designing the experiments. The control model needs to be modified to represent more advanced control techniques used in the industry like adaptive controllers. The heat transfer model inside the load is complex and currently in this research it was not studied.

- The recommended future work for the project is the incorporation of a load optimization routine. Such a routine enables the furnace utilization and improves furnace efficiency.
- Also models specifically developed to different processes enable more accurate prediction of thermal profiles and also useful for process optimization.
- Another recommendation is creating furnace specific models for different kinds of furnaces instead of two general models. For example, a different model for pit furnace, box furnace, vacuum furnace, etc.
- Another idea is using FEA as a knowledge input to model the process variations once the thermal profile of the load is calculated. This module will be helpful in designing processes accurately.

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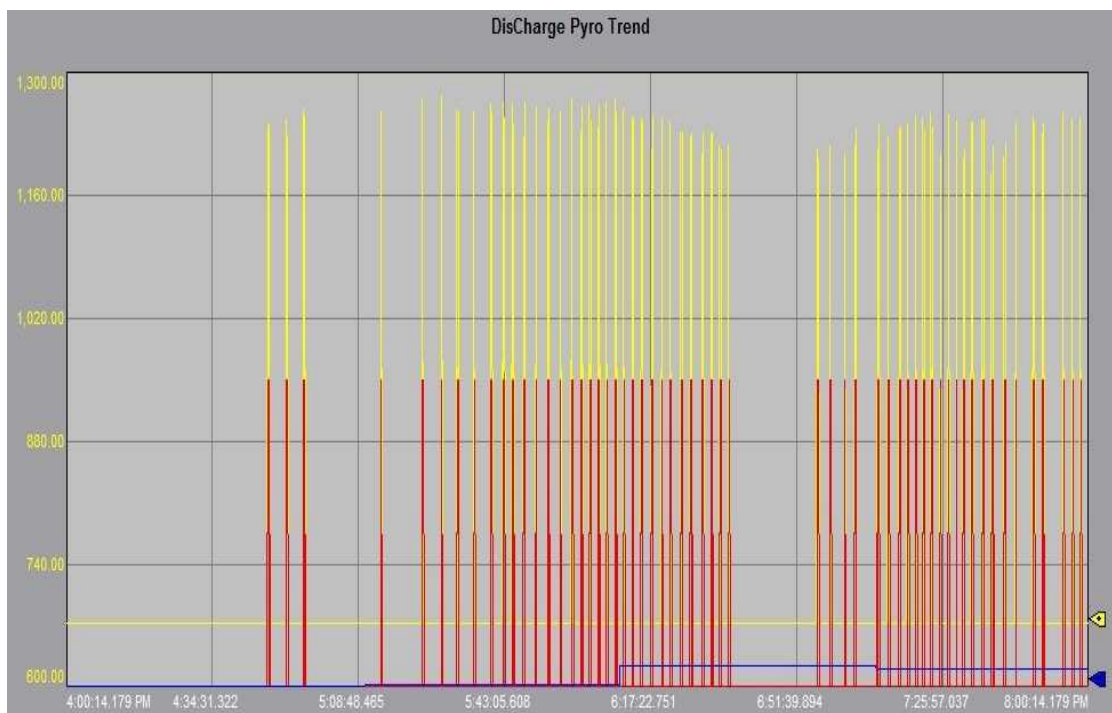
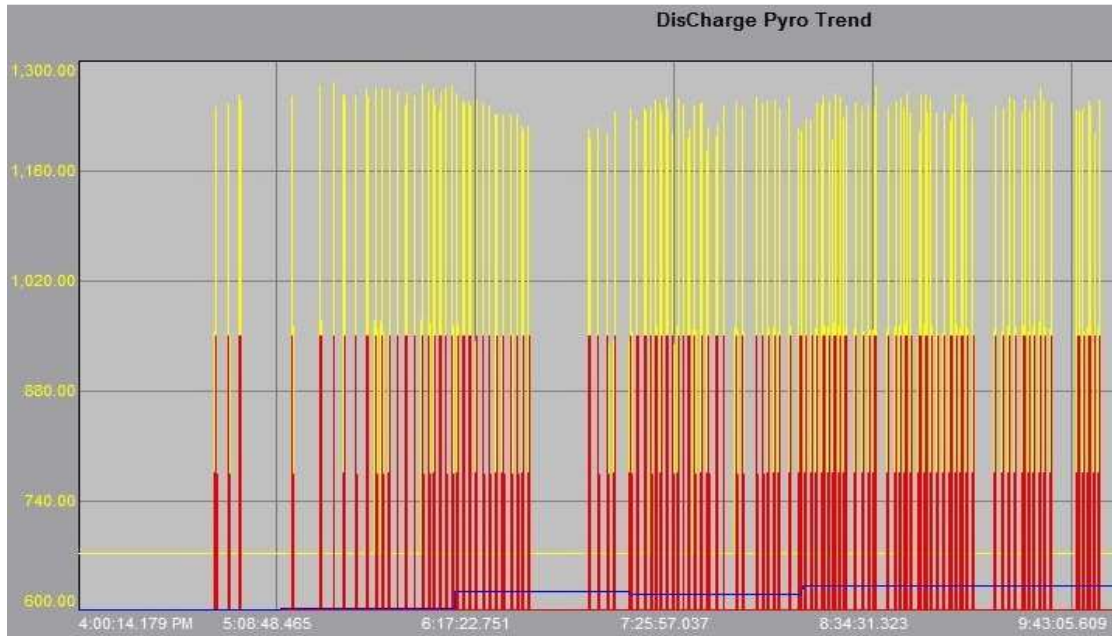
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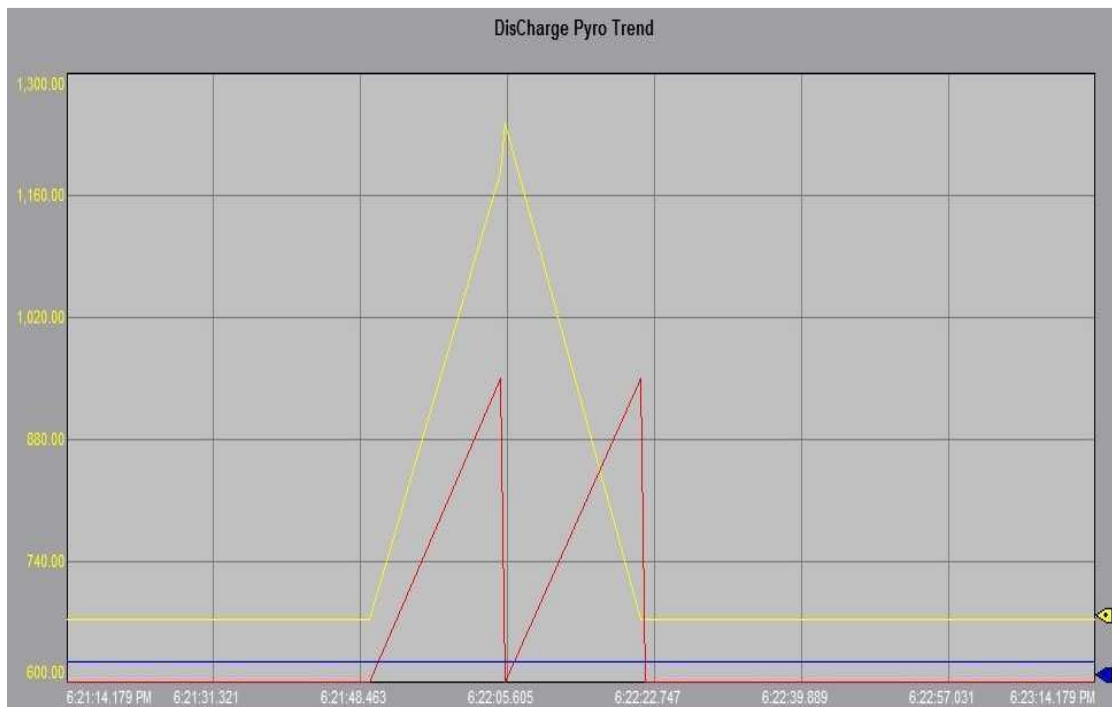
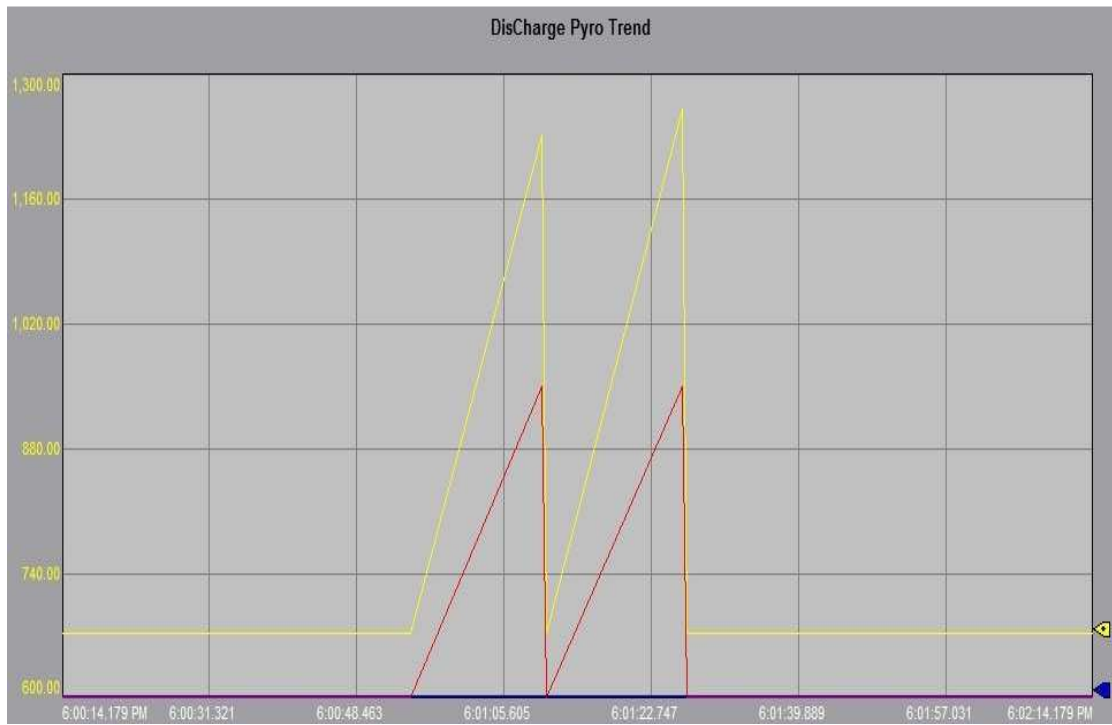
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