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Experimental Testing of a Computer Aided Heat Treatment Planning System

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Experimental Testing of a Computer Aided Heat Treatment Planning System

A
Thesis
Submitted to the faculty
of the
Worcester Polytechnic Institute
in partial fulfillment of the requirements for the
Degree of Master of Science
in
Mechanical Engineering
By

Rohit S.Vaidya
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ABSTRACT

Heat treatment is an important manufacturing process, which controls the mechanical property of metal parts, therefore contributes to the product quality. A Computerized Heat Treatment (CHT) system has been developed to model and simulate the heat transfer in furnace. When the part load and thermal schedule information is given with part and furnace specifications, the temperature profiles of parts in furnace can be calculated based on heat transfer principle. Therefore the part load and thermal schedule can be optimized to remove unnecessary delay time while the quality of heat treatment is ensured.

In the thesis, the functions of CHT are enhanced with the capability of modeling and simulating the heat treatment processes with random part load and continuous furnaces. Methods to model random load and continuous furnace have been developed. Case studies with industry real data have been conducted to validate the system and to show effectiveness of the system. The system development is also introduced in the thesis.

ACKNOWLEDGEMENT

I would like to express my gratitude to Prof. Kevin Rong, my advisor, for helping, guiding and encouraging me to complete this thesis. I also thank Prof Apelian and Prof. Richard Sisson for their enthusiastic service on the thesis committee.

I would like to thank MPI (CHTE) for providing me assistantship position in the CHTE group. I would like to thank Larry Roether, General Manager of American Heat Treating Inc for giving me an opportunity to work in their company and necessary help whenever required. I would like thank my research group member Dr. Jinwu Kang for providing technical knowledge and valuable advice whenever I needed during my research work I would like to thank Bodycote Thermal processing plant, Worcester, MA for allowing me to conduct case study in their company. I would like to thank my entire group members in the Computer Aided Manufacturing Lab for their help during my research work. . I would also like to thank the program secretary, Ms. Barbara Edilberti, for helping me out during my stay at WPI

I would like to thank my family for supporting me throughout, during my study in WPI. I would also like to thank my friends for helping me out during my study in WPI.

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CHAPTER 1. INTRODUCTION

Heat Treatment is the controlled heating and cooling of metals to alter their physical and mechanical properties without changing the product shape. 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 alter certain manufacturability objectives such as to improve machinability and formability, and to restore ductility after a cold working operation. Thus it is a very enabling manufacturing process that can not only help other manufacturing processes, but also improve product performance by increasing strength or other desirable characteristics. Steels are particularly suitable for heat treatment, since they respond well to heat treatment and the commercial use of steels exceeds that of any other materials.

1.1 Heat Treatment Processes

The term heat-treatment embraces many processes employing combinations of heating and cooling operations, applied to moulds and dies, tools and machine components so as to produce desired mechanical properties, with attendant characteristics related to particular types of 'in-service' applications. Steel is the most common metal being treated. It accounts for more than 80% of all metals.

The various processes may be broadly classified as:

a. Hardening process is intended to produce through hardened structure by quench-hardening. Hardening increases wear resistance and the strength of materials, and provides toughness after. However, the hardening often results in turning the structure of the work brittle. Besides, internal stress increases tremendously while machinability and ductility of the metal decrease. Therefore, the hardening processes need to be well studied and controlled.

b. Softening process is intended primarily to soften the material, such as annealing, and remove stresses either inherent or consequent upon prior operations, but generally resulting in a softer structure. The latter processes include stress relieving and process annealing.

c. Toughening process is intended to produce a structure possesses good strength and ductility in steels by means of normalizing. Improved machinability, grain structure refinement, homogenization and modification of residual stresses are among the reasons for which normalizing is done.

d. Case-hardening process is employed to produce a 'case' or surface layer substantially harder than the interior or core of the workpiece. They include carburizing, nitriding and induction hardening.

In this research, the heating process is studied. In order to perform a quality heat-treatment, the heat source in a furnace is heated first by the electric or fired gas (indirect or direct). The heat flux arrives at the surfaces of workpieces through radiation and convection heat transfer and arises the surfaces temperature of the workpieces. Then the temperature in the interior of a workpiece is raised in the form of conduction heat transfer. Thus, the heat treatment of workpieces is such a process that the workpieces are heated up with the radiation/convection hybrid boundary condition on the surfaces and with the conduction heat transfer interiorly. The uniformity of temperature distribution and the delay time of inside temperature will contribute to the material property control and the heat treatment quality. To optimize the temperature control and load design, it is necessary to study the detail information about the temperature distribution in furnace and workpieces as a function of time.

1.2 Problem Description

To optimize the heat treatment processes, three categories of problems need to be considered. They are,

- Quality control in the heat treatment
- Productivity
- Experience based process design and lack of a proper calculation tool.

- Quality Control in the Heat Treatment

The quality control of heat treatment for metal parts depends on many factors, including part load and furnace temperature control. It is desired to predict the heating history and temperature distributions in furnace and in workpiece so that the part load design and temperature control can be improved. Unfortunately, there is currently no comprehensive technique, which can be used to simulate heat-treating process and predict the temperature distribution of workpieces with arbitrary geometry in a loaded furnace. In current practice in heat treating industry, to ensure the quality, experimental methods have to be employed to measure the temperature in furnace space or on part surfaces.

- Productivity

The term productivity can be directly related to two terms, one being the energy consumption and the other being the cost involved in the production processes. As such there is no direct measuring method for the inside-workpiece temperature measurement in the heat-treating process. The temperature of workpieces may vary with time and location, from surface to interior. Although the workpieces temperature may be measured by thermocouples set on the workpieces surface at selected points, the interior temperature of workpieces is still unknown, especially in the middle of the furnace. In order to obtain a uniform temperature between the surface and the interior at different furnace locations, a delay of time is necessary for heat transfer from outside the load to inside the load, and heat conduction to the interior of the workpiece after the surface temperature reached the specified temperature. Nowadays this time delay is determined by experience because there is no analytical model available yet. The problem is, if the holding time relatively short, the uniform temperature between the surface and the interior cannot be obtained; but if it is too long, the mechanical property of the surface material may be changed undesirably. The either way will result in the increase in the cost involved in production, as the workpieces may have to be heat treated again.

- Experience based process design and lack of a proper calculation tool.

The part load design and furnace temperature control in heat treating industry is based on the experience for the majority of time. There are hardly any analytical tools in the heat treating industry for the calculation of the thermal schedule as well as the workpiece temperature. The most of calculations of thermal schedules are based on experience, as well as the temperature reached by workpieces. Since there is no analytical model available to predict the temperature distribution in workpieces, it is difficult to carry out an optimization of the part load. The unreasonable part load may result in a non-uniformity of temperature distributions in the workpiece. To obtain the temperature distribution and heating history of workpiece, a comprehensive mathematical model needs to be developed for the heat transfer process in heat treatment. The heat conduction in workpiece can be modeled based on the well-known heat conduction principle. The difficult is that the boundary condition is varying in time and locations of the workpiece. The boundary condition is dominated by the convection and radiation in furnace. How to integrate the related three heat transfer models into a comprehensive model for heat treatment processes is the emphasis of the research. An effective numerical method is also necessary for applying the model for solutions.

1.3. Research Objectives

After studying the heat treatment processes and the current industrial practices. The available systems for the processes was reviewed and found insufficient for the requirements for the heat-treating industry. Hence the research objectives set were as follows:

- To develop physics-mathematical models based on the heat transfer theory for the various modes of heat transfer taking place between the furnace and the workpieces and among the workpieces itself.
- To study and analyze the random load pattern of the workpieces and study their effects and develop a database containing the above model parameters that are properties of materials.
- To develop a user interface so as to obtain all the necessary data inputs or parameters for the models.
- To validate and implement the system in the current industries.

CHAPTER 2. HEAT TRANSFER PRINCIPLE

This chapter deals with the various heat treatment principles, which are divided into conduction, convection and radiation. In this chapter we will briefly study the previous research that have been done and present the scope of the research.

2.1 Heat Transfer Principle

Heat is a form of energy and is transported from one body to another due to the temperature differences in the bodies. The heat can transfer by one, or by a combination of three separate modes known as conduction, convection and radiation. Conduction occurs in a stationary medium; convection requires a moving medium; and radiation occurs in absence of any medium, distinguishing it as part of electromagnetic spectrum. Although they are distinct processes, they can occur together.

The heat generated in a diesel engine, for example, is transferred from the combusted gas to the steel cylinder walls by the combined action of radiation and convection. Heat flows through the cylinder walls by conduction. In turn, the outer surface of the wall is cooled by convection, and so some extend radiation, owing to water circulating in the cooling passages. The physical processes that govern conduction, convection and radiation are quite different, leading to have a different approach for each process analysis.

2.1.1 Conduction heat transfer

Conduction occurs in a stationary medium. It is most likely to be of concern in solids, although conduction may present to some extent in gases and liquids. In the solids the mechanism of conduction is due to the vibration of the atomic lattice and the motion of the free electrons, the latter generally being a more powerful effect. The metallic solids are good conductors because of the contribution made by available free electrons.

Conduction is governed by Fourier's law, which states, "the rate of flow of heat through a simple homogenous solid is directly proportional to the area of the section at right angles to the direction of heat flow, and to change of temperature with respect to the length of the path of the heat flow [1].

It is represented mathematically by the equation:

$$Q \,\alpha\, A \frac{dt}{dx} \tag{1}$$

where Q = heat flow through a body per unit time (watts);

A = surface area of heat flow perpendicular to direction of flow (m^2);

dt = temperature difference of the faces of body (homogenous solid) of thickness dx' through which heat flows, (°C or K); and

dx = thickness of body in the direction of flow (m).

Thus,

$$Q = -\lambda.\, A \frac{dt}{dx} \tag{2}$$

where λ = a constant of proportionality and known as *thermal conductivity*

The negative sign is to take care of the decreasing temperature along with the direction of increasing thickness or the direction of the flow. The temperature gradient dt/dx is always negative along positive x direction and, therefore the value of Q become positive.

2.1.2 Convection heat transfer

Heat transfer due to medium in form of liquid or gas occurs in convection heat transfer. The convection heat transfer equation between a surface and an adjacent medium is prescribed by *Newton's law of cooling* [1].

$$Q = h\; A\,(t_s - t_f) \tag{3}$$

where, Q = rate of convective heat transfer (watts);

A = surface area exposed to heat transfer (m^2);

t_s = surface temperature (°C or K);

t_f = fluid temperature (°C or K); and

h = coefficient of convection heat transfer (W/m^2-K)

The coefficient of convection heat transfer *'h'* is defined as "the amount of heat transmitted for a unit temperature difference between the fluid and unit area of surface in unit time". The value of *'h'* depends on thermodynamic properties (viscosity, density, specific heat etc), nature of fluid flow, and geometry of the surface and prevailing thermal conditions.

2.1.3 Radiation heat transfer

Radiation heat transfer is concerned with the exchange of thermal radiation energy between two or more bodies. Thermal radiation is defined as electromagnetic radiation in the wavelength range of 0.1 to 100 microns (which encompasses the visible light regime), and arises as a result of a temperature difference between 2 bodies).

No medium need exist between the two bodies for heat transfer to take place (as is needed by conduction and convection). Rather, the intermediaries are photons, which travel at the speed of light.

The heat transferred into or out of an object by thermal radiation is a function of several components. These include its surface reflectivity, emissivity, surface area, temperature, and geometric orientation with respect to other thermally participating objects. In turn, an object surface reflectivity and emissivity is a function of its surface conditions (roughness, finish, etc.) and composition.

The equation for radiative heat transfer between a surface and its surroundings is [1]:

$$q_{rad} = E \sigma A (T_s^4 - T_{sur}^4) \tag{4}$$

where: q_{rad} = heat flux in watts (W);

E = emissivity. E is a ratio that describes how well a surface emits radiation compared to a perfect emitter

$\sigma = 5.67 \times 10^{-8}$ W / (m^2 x K ^{4}). σ is the Stefan-Bolztmann constant and characterizes radiation from a perfect emitter.

A = surface area in meters squared (m^2).

T_s = Surface temperature in Kelvin (K).

T_{sur} = Surrounding temperature in Kelvin (K).

2.2 Previous Research

The product quality and productivity are greatly affected by heating control. To solve this problem, the key point is the prediction of heating history and temperature distributions in furnace and in part [1]. Generally there are two well-known methods for the analysis of heat transfer processes in a furnace: numerical method and analytical method. Analytical method is more common for simply cases in industrial application. A “virtual sphere” concept and experience/analytical based equations are developed to estimate the equilibration time and heating rates in parts loaded in a furnace [2]. Analytical solutions for the radiative heat transfer in box-shaped furnaces and cylindrical furnaces were presented [3, 4]. A method of fitting general function form was used to estimate the temperatures at the specified points in box-shaped and cylinder furnaces so as to replace the temperature measurement. Both the part temperature and the furnace temperature were predicted in ref. [5] without consideration of load patterns. These kinds of studies can only deal with some regular shapes of parts without consideration of load patterns, and the temperature distribution inside the parts is assumed uniform.

Taking under considerations all the parameters required for the heat treatment developed the Computerized Heat Treatment for batch furnace (CHT-*bf*) is a software tool used to simulate the parts heating process design and predict the heat-treating results. The simulating results can be used to evaluate the part loading pattern or thermal schedule.

There are five modules in the system

- Process design module, including part load design, thermal schedule design, part and furnace definition, and some process parameters definition;
- Temperature calculation and evaluation module, including both workpiece and furnace temperature calculation;
- Database/Knowledge system, including data search, data management for workpiece, furnace, part loads, and thermal schedule;
- Output, the results process and graphic/evaluation output;
- CAD based user interface: used for information input/output and interactive

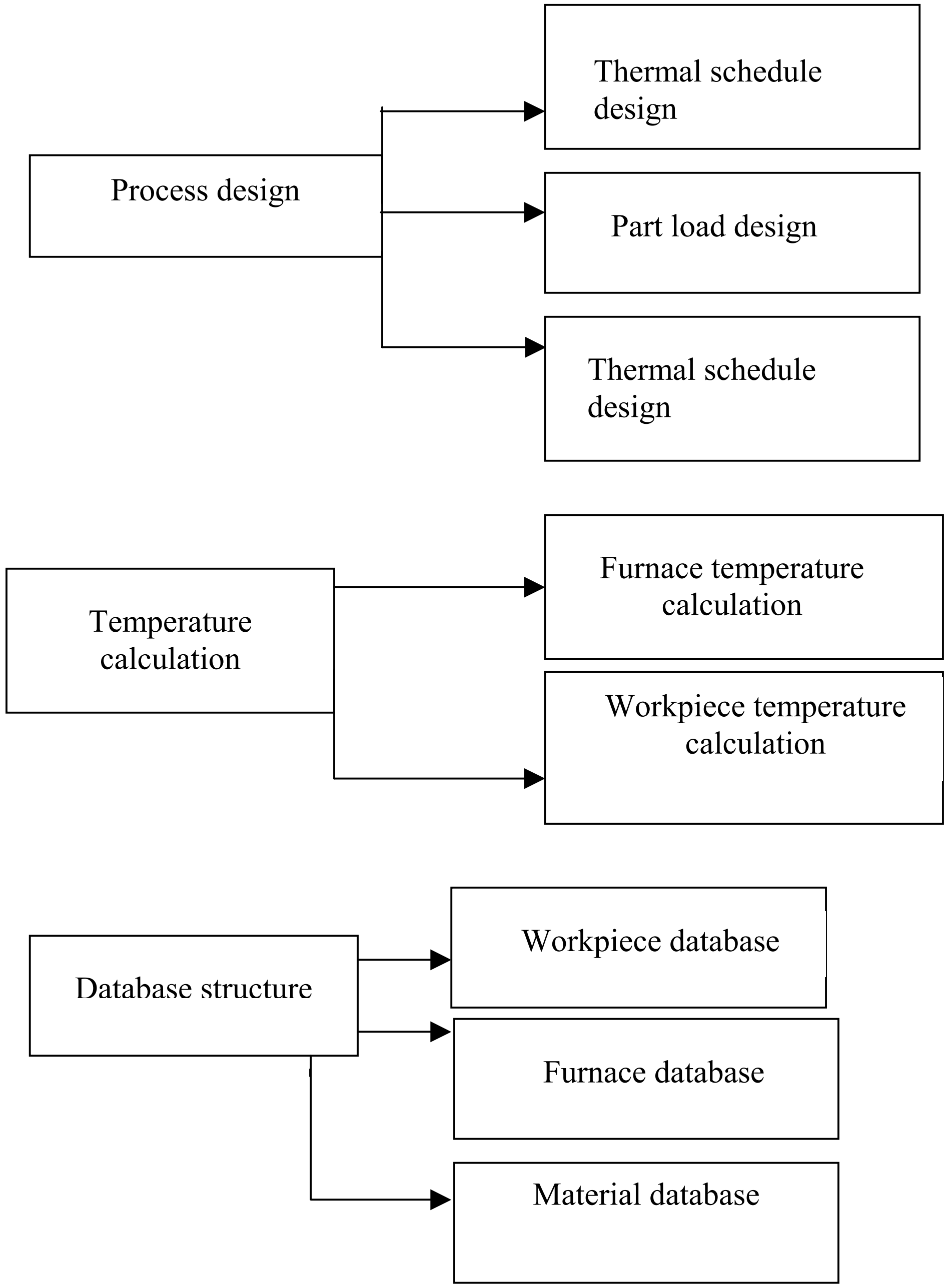


Fig.1 Flow chart showing various modules of the CHT-*bf* system

The system main functions include:

- The simulation of heating process of workpieces in loaded furnace;
- The calculation of the furnace average temperature for various types of furnaces;
- The calculation of energy balance for furnace heat-treating process;
- The design and optimization of the thermal schedule and part loading; and
- Database management system for heat-treat process design.

The objective of this research is to establish a knowledge-based computer-aided heat treat planning software system for the heat treatment process optimization. The software was basically designed by taking the arranged load pattern of the workpieces under consideration, but in actual cases many times it was found that the load pattern to be randomly placed. This leads to the addition of the random load model in the system.

2.3 Thesis Focus:

The thesis is basically can be categorized into two parts, random load modeling and continuous furnace modeling.

1. Random Load Modeling

There are hardly any studies about the heat transfer in random load pattern of workpieces in heat treatment industry. Actually the heat transfer in random load pattern is very complicated because of the complexity of the packing mechanism itself. The heat transfer mechanism has not been fully understood. Therefore there arises a need to study theses random load patterns.

2. Continuous Furnace.

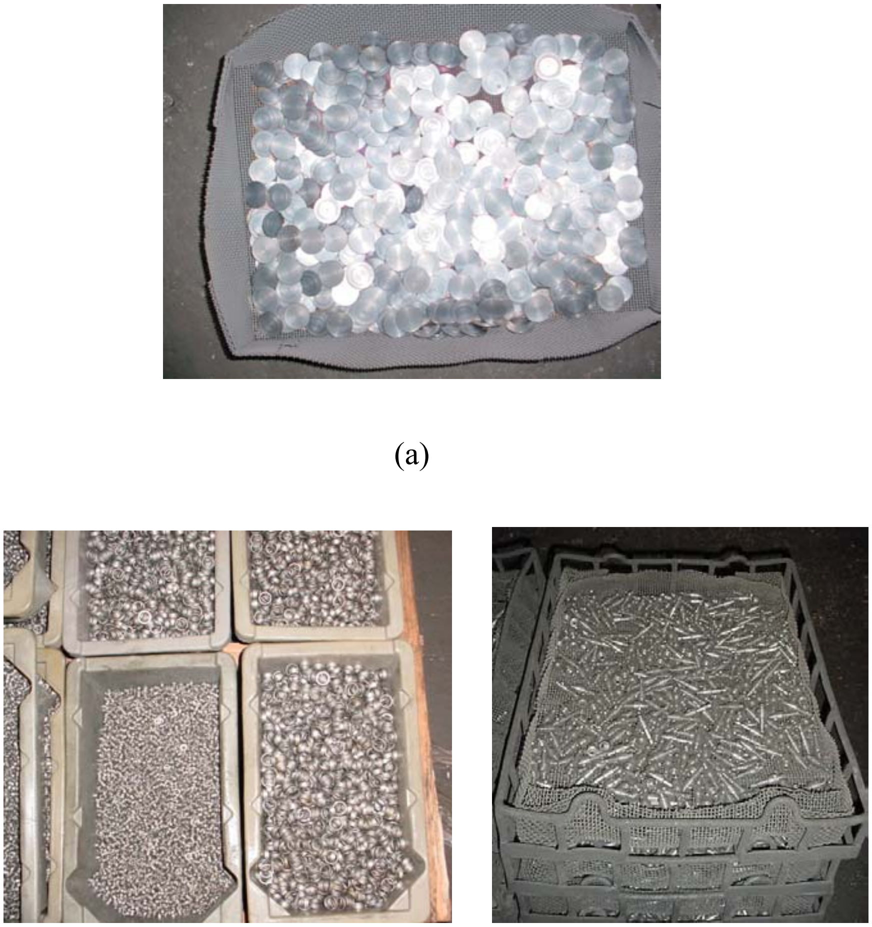
Furnace technology, economics and part quality influence the decision on whether to use a continuous or a batch operation. The economics questions center around cost of ownership, which can include initial cost, operating costs, repair costs, product yields and return on investment. Quality issues often are associated with process stability, product quality and consistency, while technology focuses on ease of operation, process definition, thermal cycles, temperature requirements, atmosphere conditions, weight of product and desired throughput. The questions and their relative importance vary from industry to industry, company to company and person to person. But a universal set of questions always concerns continuous furnace design. Thus the continuous furnaces more or less are the part of almost every heat treatment industry. This leads to research and develop an analytical tool for the calculation of temperature in the continuous furnace.

CHAPTER 3. RANDOM LOAD MODEL

The Computerized Heat Treatment for batch furnace software (CHT-*bf*) was developed with the view to study and predict the heat treatment process. The earlier version of CHT-*bf* had more emphasis on the aligned load pattern, thus the next step was considering the Random load pattern in the system. In this chapter, the heat transfer problem of random load pattern was systemically reviewed and analyzed. Two practical methods have been studied and applied to the system.

3.1 Random Load Pattern

In heat treatment production, some small workpiece are usually heat treated in random load pattern. Here are some examples of random load pattern, as shown in Fig. 2.



(a)

(b) (c)

Fig. 2 Random load pattern examples

3.2 Review Studies on Random Arrangement

There are hardly any studies about the heat transfer in random load pattern of workpieces in heat treating industry. Actually the heat transfer in random load pattern is very complicated because of the complexity of the packing mechanism itself. The heat transfer mechanism has not been fully understood. Here some related studies about random packing of particles and the inside heat transfer are reviewed.

3.2.1 Conduction between small particles

The similar problem, the heat transfer in random packed particles, such as metal powder in powder metallurgy, has been widely studied for a long time.

1) Thermal Conductivity in metal powder

To study the thermal conductivity of powder, equation for two-mixed phase was derived by Maxwell as [2]

$$\lambda_{Ag} = \lambda_M \left(\frac{2\lambda_D + \lambda_M + P_D(\lambda_D - \lambda_M)}{2\lambda_D + \lambda_M - 2P_D(\lambda_D - \lambda_M)}\right) \tag{5}$$

where $\lambda_{Ag}, \lambda_M, \lambda_D$ are the thermal conductivities of the aggregate, matrix and disperse phase, respectively, P_D is the volume fraction of the disperse phase.

For powder, the matrix phase is air, so its thermal conductivity can be simplified as follows,

$$\lambda_p = \lambda_A \left(\frac{3}{P_A} - 2\right) \tag{6}$$

where λ_p, λ_A are the thermal conductivity of the powder and air, respectively, P_A is the volume fraction of the air.

The thermal conductivity of powder just relates to the thermal conductivity of air and the volume fraction of air over the total volume. It can be seen from Fig.2 that the thermal conductivity of powder is very small as the air fraction exceeds around 5%. As powder gets compressed or fused, the thermal conductivity is very close to the value obtained by additivity rule, which means the mixture's thermal conductivity is the weighted value by volume ratio. Fig. 3 illustrates the influence of porosity on thermal conductivity of a loose powder.

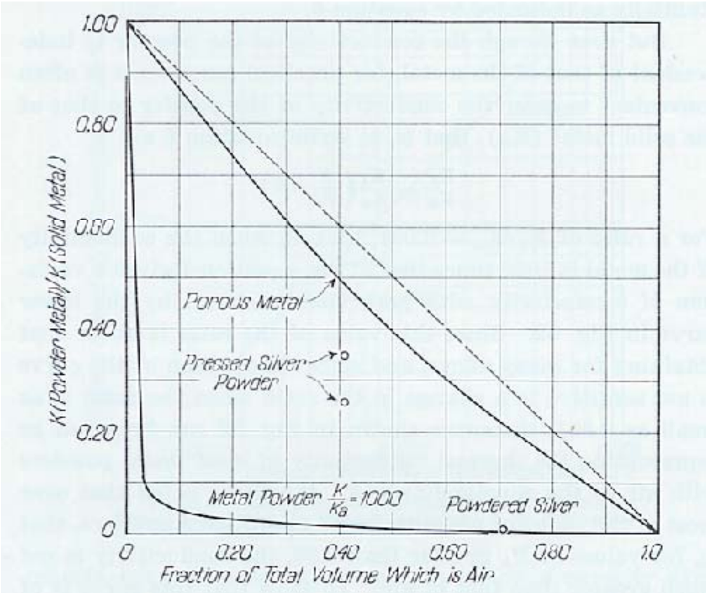


Fig. 3 The influence of porosity on thermal conductivity. The upper curve represents the variation for a sintered powder; the lower curve represents that of a loose powder [2].

2) Thermal conductivity between particles

The thermal resistance between particles are studied and compared with variations of deformation of the contact point by Finite Element Method (FEM) [3]. The research showed that the thermal resistance decreases with the increase of deformation of the contact point, i.e., the thermal conductivity in metal powder increases with the increase of density that means increasing deformation. When the deformation (strain ratio or contact radius) is very small, for example 0.1, the thermal resistance is 10 times that of the metal, i.e., the thermal conductivity between these two spheres are just one tenth of the solid phase of the metal.

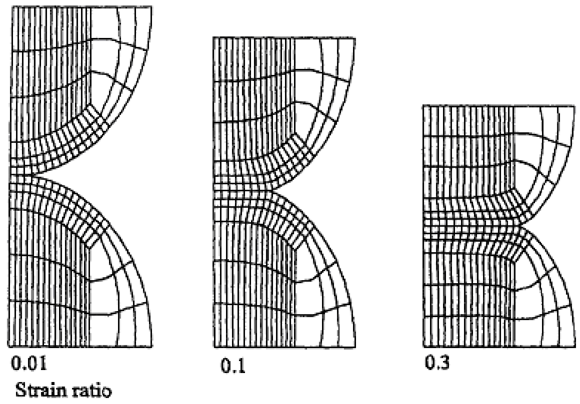


Fig. 4 Enmeshment of contact sphere with different strain ratio [3]

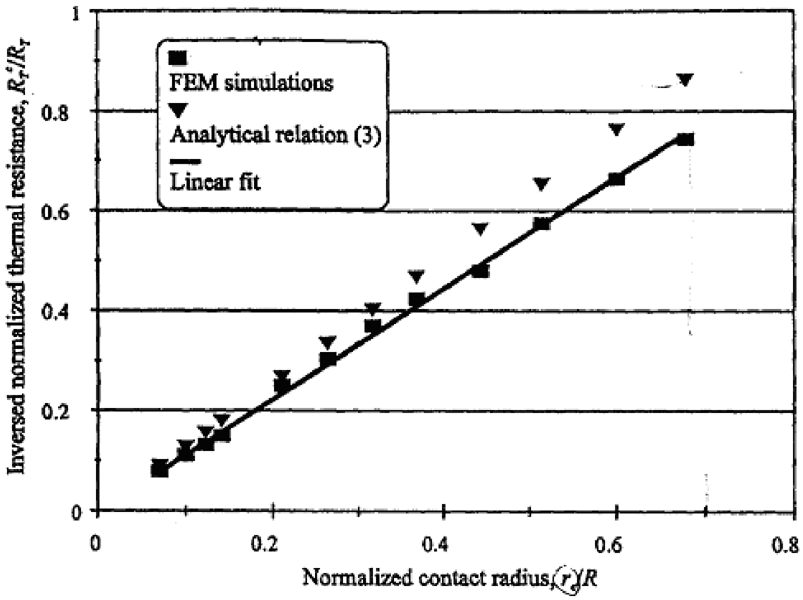


Fig. 5 Normalized thermal resistance as a function of normalized contact

3.2.2 Radiation heat transfer in powder

The radiative conductivity in metal powder was evaluated by a ray tracing method [4]. The results show that the radiation contribution is negligible compared to the solid phase conduction in powder.

3.2.3 Construction of random load patterns

If the three-dimensional random load pattern model is constructed the heat transfer in random load pattern can be solved by finite difference method (FDM) or FEM. Here some studies about the construction of random load pattern are presented.

The study of particles packing is of industrial importance to determine the porosity in geotechnical engineering of soils and rock fill, mining and mineral engineering, and in powder technology. Because of complexity it is still limited to random packing of regular shapes, such as cubic, sphere, rod, tetrahedral and etc. There are usually two kinds of methods for random packing of particles, one is sequential algorithm (or Ballistic deposition technique), and the other is collective algorithm (space filling). The first one is that the particles are randomly dropped in the container one after another. Under the influence of gravitational forces, the dropped particle will roll over the existing particles until it reaches a stable position. The second one is that particles of zero size are first randomly placed in the container. Following this initial distribution, sizes of the particles are constantly increased. They are moved apart if overlap occurs between two particles just in touch [5].

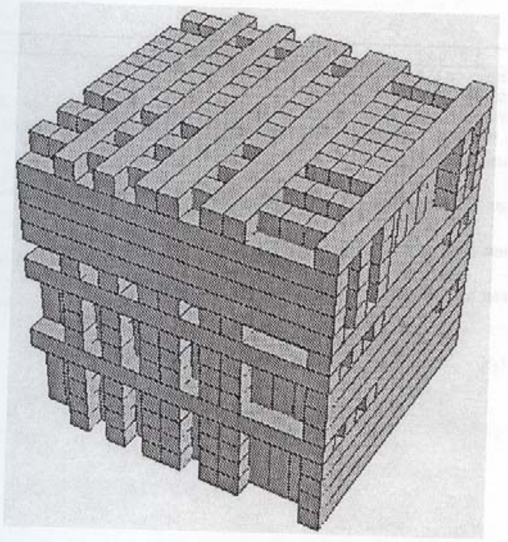


Fig. 1. An example of the configuration of completely packed rod ($a = 15$).

Fig. 6 An example of the configuration of completely packed rods (a=15) [6]

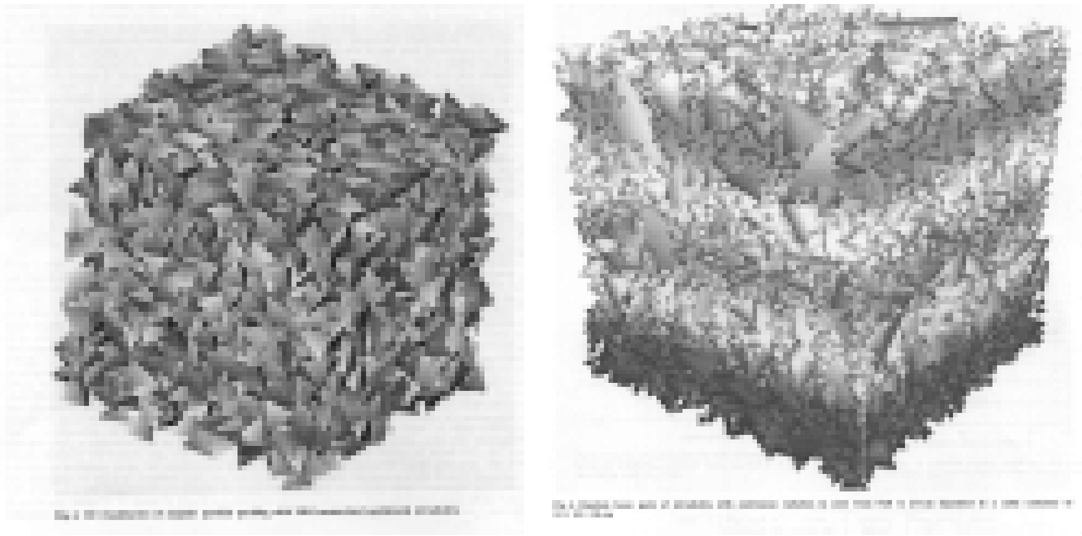


Fig.7 Random package of mono-sized tetrahedral and multi-sized tetrahedral [5]

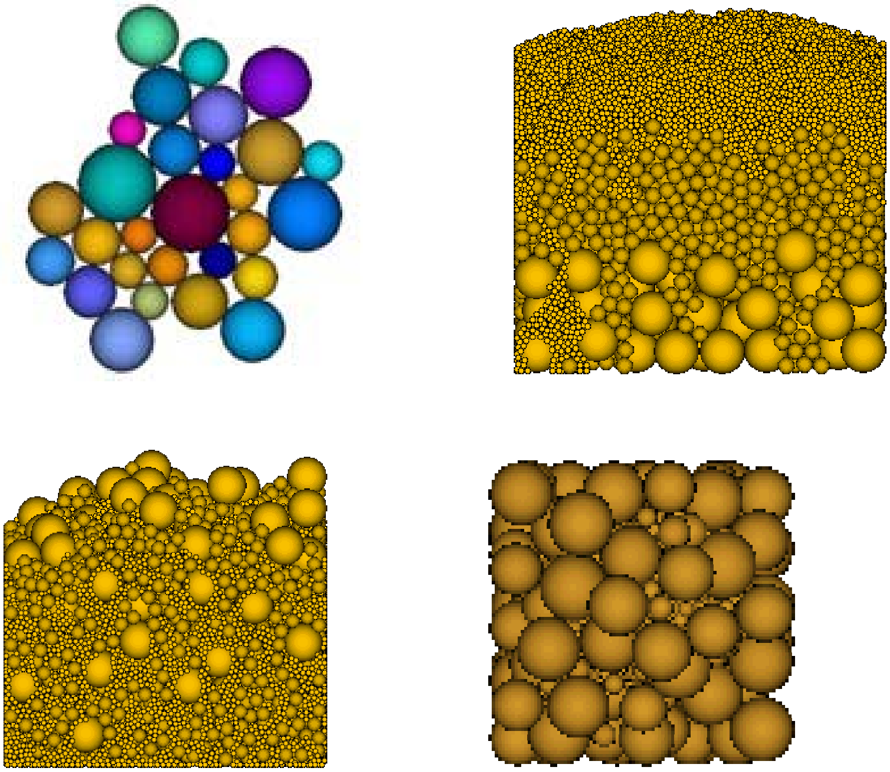
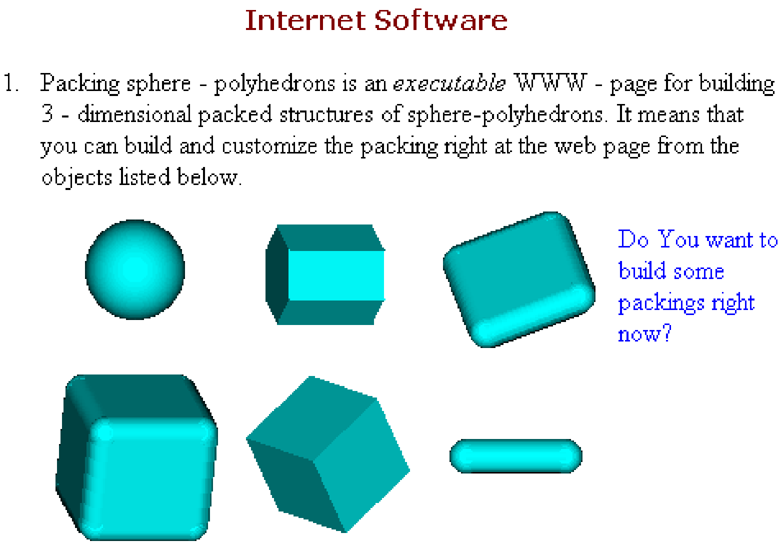


Fig. 8 Random load pattern examples [7]



Internet Software

1. Packing sphere - polyhedrons is an *executable* WWW - page for building 3 - dimensional packed structures of sphere-polyhedrons. It means that you can build and customize the packing right at the web page from the objects listed below.

Do You want to build some packings right now?

Fig. 9 Random load pattern software [7]

3.3 Mathematical Model for Heat Transfer in Random Loads

There are mainly two kinds of methods for random load pattern, one is the effective thermal conductivity method, and the other one is separate calculation of conduction, convection and radiation inside the load. The effective thermal conductivity means that the conduction, convection and radiation are totally considered apparent conduction; there is no need to understand the effect of each heat transfer type. It can be based on measured results or numerical simulation results. The second method is based on the understanding the mechanisms of the heat transfer inside the load.

3.3.1 Method 1: Effective Thermal Conductivity Method

The flowchart of this method is shown in Fig. 10. The first step is to calculate the effective thermal conductivity. And then it is used to predict the heating process of the load. There are two ways to calculate the effective thermal conductivity, one is based experimental measured result, and the other one is based on the numerical method.

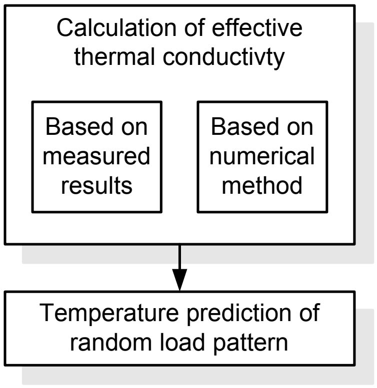


Fig. 10 Flowchart of effective thermal conductivity method

(1) Based on measured results

Because of the complicity of heat transfer inside the load, the simplest method is to design a sample with just one dimensional heat transfer involved and measure the temperature variations with time of the surface point and the center point. The effective thermal conductivity can be then calculated by reverse method based on the measured results. It is better to use specially designed load sample. Otherwise the real load in production can also be used. So the heat transfer will be not just one dimensional. Thus calculation of effective thermal conductivity based on specially designed load sample and real load sample is as follows

(a) Specially designed load sample

The specially designed load sample can be a long cylinder as shown in Fig. 11.The experiment request is as follows:

- Sample shape: cylinder ($L>10R$),
- The furnace temperature remains a constant value,
- Measure the surface temperature T_w and center temperature T_c.
- Enough workpieces are randomly packed inside the container same way as industrial production.

The ratio of length to the radius of the load sample size is greater than 10 is to make sure there is just heat transfer in radial direction and no heat transfer in axial direction.

- *Tw* = Surface Temperature of the cylinder
- *Tc* = Central Temperature of the cylinder
- *To* = The initial temperature of the cylinder
- *L* = Length of the cylinder
- *R*= radius of the cylinder

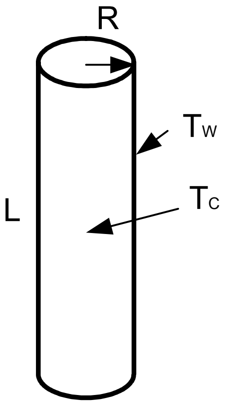


Fig. 11 The specially designed load sample

The furnace temperature is kept at constant value, and then the surface temperature of the cylinder *Tw* can be assumed as constant. So, the equation for the temperature at an arbitrary point inside the load is [8].

$$T(X(d),\tau) = Tw + (To - Tw).2\sum_{i=1}^{\infty} X^m \frac{J_{-m}(\mu_i X)}{\mu_i J_{1-m}(\mu_i)} e^{-\mu_i^2 \tau} \tag{7}$$

where $X = \frac{R-d}{R}$, $\tau = \frac{\alpha t}{R^2}, \alpha = \frac{\lambda_{eff}}{\rho c}$, t is the time, d is the distance from the surface, ρ is the average density of the load, c is the specific heat, λ is the thermal conductivity, $J_{-m} = (-1)^m J_m$.

For the cylinder, *m=0*. Then

$$T(X,\tau) \approx Tw + (To - Tw) \times 2 \frac{J_0(\mu_1 X)}{\mu_1 J_1(\mu_1)} e^{-\mu_i^2 \tau} \tag{8}$$

At the center of the load *d =L* and thus *X=0*. The μ_i is the root of $J_0(\mu_i) = 0$, then

μ_i = 2.4048, 5.5201, 8.6537, 11.7915, 14.9309,

As the higher term of exponent can be omitted, then

$$T_c \approx Tw + (To - Tw) \times 2 \frac{J_0(0)}{2.4048 J_1(2.4048)} e^{-\mu_1^2 \tau} \tag{9}$$

$$T_c \approx Tw + 0.52(To - Tw) e^{-2.4048^2 \frac{\lambda_{eff}.t}{\rho.c.R^2}} \tag{10}$$

So, the only unknown, the effective thermal conductivity λ_{eff} can be calculated by the measured load surface temperature and center temperature by

$$\lambda_{eff} = -0.173 \frac{\rho.c.R^2}{t} \ln \frac{1.923(Tc - Tw)}{To - Tw} \tag{11}$$

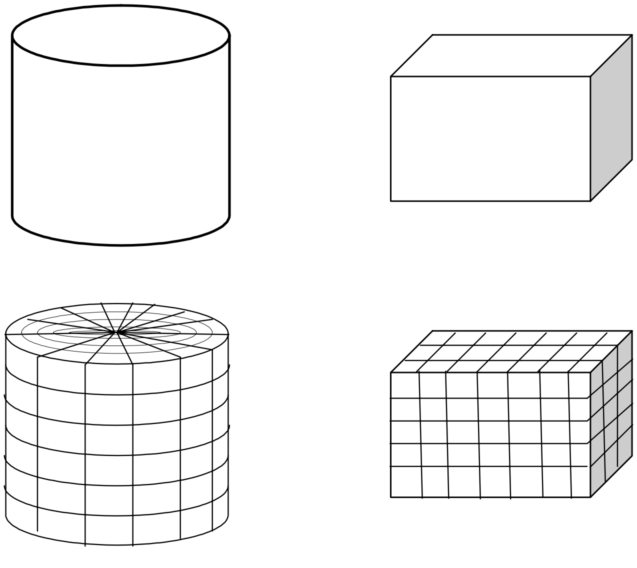
(b) Real load sample

If specially designed load sample is not available two kinds of real load shapes, cubic and round can be applied. For real load samples the heat transfer is not limited in one direction, so, three-dimensional finite difference method should be used. The measurement requests: temperatures of the outside layer and center of the load.

First of all, the whole load is enmeshed as shown in Fig. 12. The whole load is usually of very simple shape, so the enmeshment is done directly by the program. No need is necessary to construct solid geometrical model by CAD software. Then the calculation of effective thermal conductivity can follow the procedure as shown in Fig. 12.

Firstly, give an initial value for effective thermal conductivity. Then calculate the temperature of the center point by the measured temperatures of the outside layer as boundary condition. Compare the calculated temperature and measured temperature of the center point. If there is a great difference iterate the calculation with a new value for thermal conductivity until the error falls into the reasonable range. And then the effective thermal conductivity is obtained. Usually many iterations of calculation are necessary to get the exact thermal conductivity. Here convection and radiation effects are also included in the thermal conductivity.

For a round load equation (8) can be used, while for a cubic load shape, equation (9) can be used for heat transfer calculation. The discretized equations are equation (10) and (11), respectively. Here it is assumed there is no heat transfer in the circumferential direction in the round load sample.



(a) Cylinder (b) Cubic

Fig. 12 Real load samples

$$\rho c\frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right) \tag{12}$$

$$\rho c \frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{13}$$

$$T_{i,j}^{m+1} = T_{i,j}^{m} + \frac{\lambda \cdot \Delta t}{\rho \cdot c}\left(\frac{T_{i+1,j}^{m} - 2T_{i,j}^{m} + T_{i-1,j}^{m}}{\Delta r^2} + \frac{T_{i+1,j}^{m} - T_{i,j}^{m}}{r\Delta r} + \frac{T_{i,j+1}^{m} - 2T_{i,j}^{m} + T_{i,j-1}^{m}}{\Delta z^2}\right) \tag{14}$$

$$T_{i,j,k}^{m+1} = T_{i,j,k}^{m} + \frac{\lambda \cdot \Delta t}{\rho \cdot c}\left(\frac{T_{i+1,j,k}^{m} - 2T_{i,j,k}^{m} + T_{i-1,j,k}^{m}}{\Delta x^2} + \frac{T_{i,j+1,k}^{m} - 2T_{i,j,k}^{m} + T_{i,j-1,k}^{m}}{\Delta y^2} + \frac{T_{i,j,k+1}^{m} - 2T_{i,j,k}^{m} + T_{i,j,k-1}^{m}}{\Delta z^2}\right) \tag{15}$$

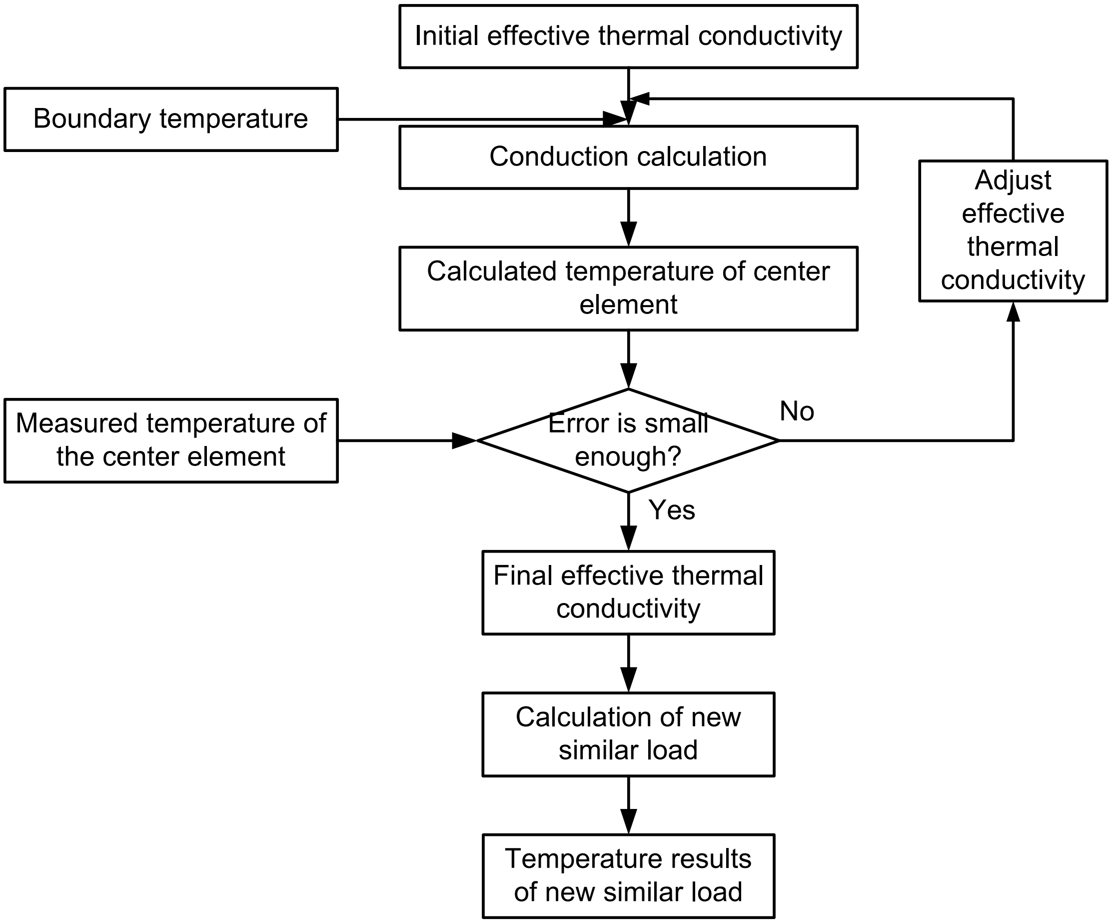


Fig. 13 Flowchart of effective thermal conductivity method based on measured results

(2) Based on numerical method

If a sample region of the three-dimensional model of random load pattern is constructed, the effective thermal conductivity can be calculated by finite difference method. Suppose the random load pattern model is constructed as Fig. 13, then enmesh the model, the enmeshment is shown in Fig. 14. Suppose one pair of two opposite sides is adiabatic, the other pair of the two opposite sides is suddenly exerted to different constant temperatures T_1 and T_2. Then heat transfer inside the region will occur under the drive of temperature gradient. The constant temperatures at two sides serve as boundary condition. In the finite difference model there are two kinds of elements, part and air. Thus, the thermal properties of all elements are known. Then the heat transfer between the two sides can be calculated by equation (11) (For three-dimensional problem, two pairs of opposite sides are assumed as adiabatic). As the heat transfer between the two sides reach static state, the heat flow between the two sides can be calculated by equation (12).

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{(\lambda_i + \lambda_j)}{2} \frac{A_i (T_{i+1,j} - T_{i,j})}{\Delta x} \tag{16}$$

where Δx is the element size in X direction, Ai is the surface area of an element perpendicular X direction, λi is the thermal conductivity of i element, m and n are the numbers of elements in X and Y directions, respectively.

Then the effective thermal conductivity can be calculated by

$$\lambda_{eff} = \frac{Q}{\dfrac{A(T_2 - T_1)}{L}} \tag{17}$$

where A is the total side surface area.

When the thermal effective thermal conductivity is obtained, then it can be used back to calculate the heat transfer in the same load pattern.

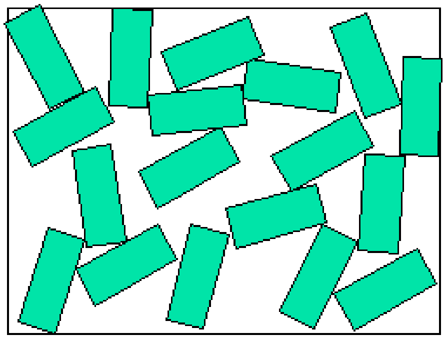


Fig.14 Random load pattern model

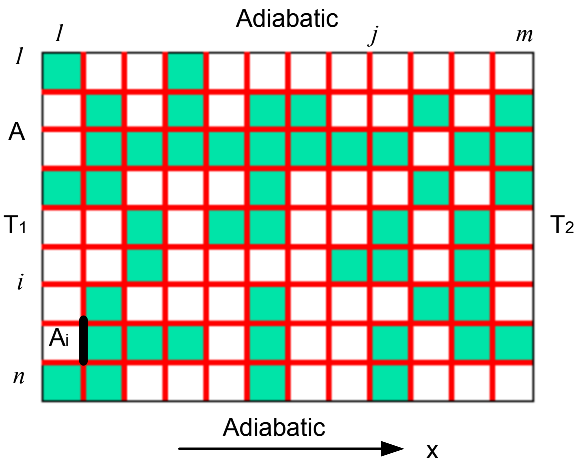


Fig.15 Enmeshment of random load pattern

This bottleneck of this method is how to construct the 3-D geometrical model of the random load pattern. This method is mentioned here just as a possible method in future.

3.3.2 Method 2: Assumption of orderly arrangement

For the random load pattern, if it shaken more and more times the load will seem more like orderly arrangement and more workpieces can be added. Thus there is some kind of intrinsic relationship between random load pattern and arranged load pattern. Then the random packing can be assumed to be an arranged one. The numbers of row, column and layer can be obtained by dividing the size of the fixture and workpiece size. Then the heat transfer in random load packing can be calculated by integration of radiation, convection and conduction models. Convection can be calculated by the method in report 01-2 [12] and the radiation among workpieces by the radiation model proposed in report 02-1 [10]. Usually the workpiece in the random load pattern is very small; therefore it can be dealt as lumped capacitance. Therefore there is no conduction inside workpiece. The only problem is the conduction inside the load, i.e. the conduction between workpiece and workpiece. It will be addressed as follows.

a) Conduction model

Usually the contacts among workpieces are point to point or line to line. Thus, here the comparisons of radiation and conduction between contact spheres; contact cylinders are carried out to evaluate their effects.

(1) Sphere to sphere

Assume the contact spheres are shown as Fig. 15. The contact radius is denoted by *ar,* where *a* is called the stain ratio, *r* is the radius of the spheres.

The temperature increase of sphere *i* contributed by radiation from sphere *j* is

$$\begin{aligned}(\Delta T_i^{m+1})_{radiation} &= \frac{\sigma\varepsilon F v A}{\rho V c}((T_i^m)^4 - (T_j^m)^4)\Delta t \\ &= \frac{\varepsilon\sigma}{2r\rho c}\Delta T_{ij}^{\ m}(T_i^m + T_j^m)((T_i^m)^2 + (T_j^m)^2)\Delta t\end{aligned} \tag{18}$$

where *p*, *c* are the density and specific heat of the sphere, respectively, *Ti* and *Tj* are the temperatures of sphere *i* and sphere *j*, *t* is the time step, *Fv*, the view factor of sphere *i* to *j*, is assumed to be *1/6* for spatial symmetry, *A* is the surface area of the sphere, the upper note *m* means the time step.

The temperature increase contributed by conduction is

$$\begin{aligned}(\Delta T_i^{m+1})_{conduction} &= \frac{\lambda A_{contact}}{2r\cdot\rho\cdot cV}\Delta T_{ij}^m\Delta t \\ &= \frac{\lambda}{2r\rho c}\frac{\pi(ar)^2}{\frac{4}{3}\pi r^3}\Delta T_{ij}^m\Delta t \\ &= \frac{\lambda}{\rho c}\frac{3a^2}{8r^2}\Delta T_{ij}^m\Delta t\end{aligned} \tag{19}$$

where, $A_{contact}$ is the contact area between the two spheres, λ is the thermal conductivity of the sphere.

Then the ratio of the temperature increase contribution by radiation to conduction is

$$\frac{(\Delta T_i^{m+1})_{radiation}}{(\Delta T_i^{m+1})_{conduction}} = \frac{4r\varepsilon\sigma(T_i^m + T_j^m)((T_i^m)^2 + (T_j^m)^2)}{3\lambda \cdot a^2} \tag{20}$$

For carbon steel, λ = 40W/m-K. The strain ratio *a* is very small because we assume there is stiff contact. Assume *Ti* = 300K. The ratio vs. radiuses of the sphere, temperature of Tj and strain ratio are plotted out in Fig. 16.

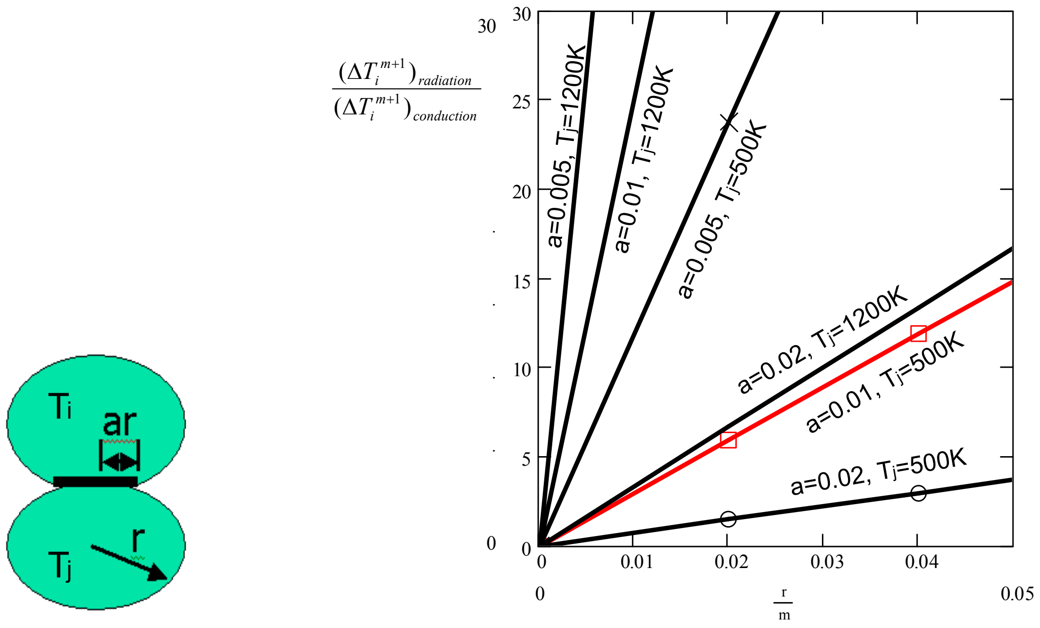


Fig. 16 Comparison of radiation and conduction between contact spheres

(2) Cylinder to cylinder

The contact cylinders are shown in Fig. 16. The contact radius is denoted by *ar,* where *a* is called the stain ratio.

By the same way as contact spheres the ratio of the contribution of temperature increase of cylinder *i* by radiation to conduction from cylinder *j* is

$$\frac{(\Delta T_i^{m+1})_{radiation}}{(\Delta T_i^{m+1})_{conduction}} = \frac{r\varepsilon\sigma(T_i^m + T_j^m)((T_i^m)^2 + (T_j^m)^2)}{3\lambda \cdot a} \tag{21}$$

For carbon steel, λ = 40W/m-K. Assume *Ti* = 300K. The ratio vs radius of the cylinder, temperature *Tj* and strain ratio are plotted out in Fig. 17.

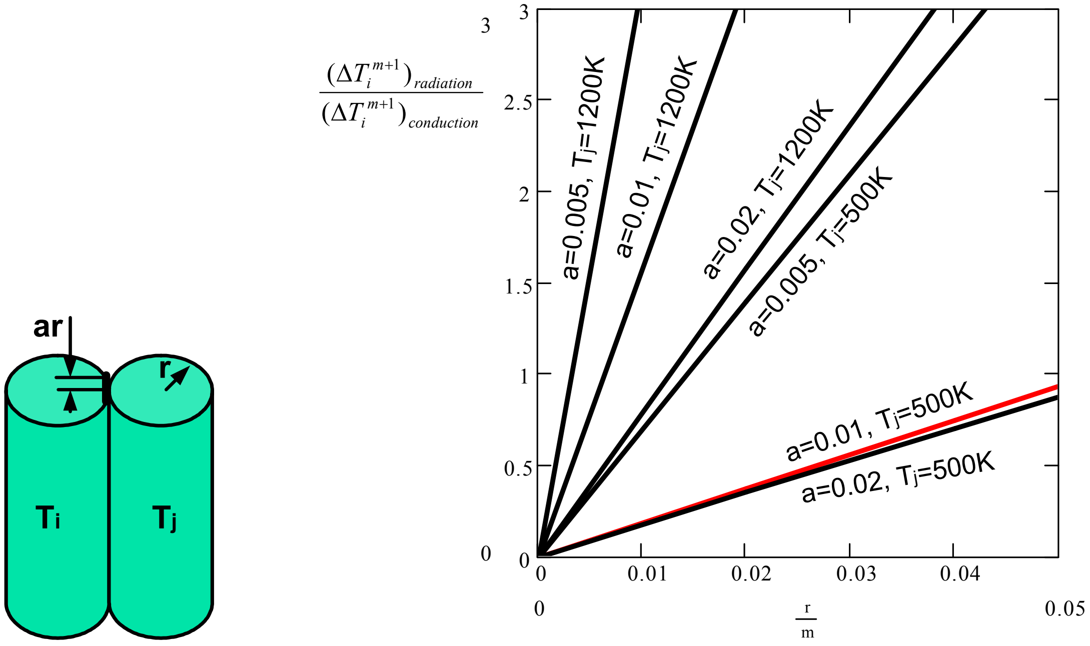


Fig. 17 Comparison of radiation and conduction between cylinders

It can be seen from Fig. 16 and Fig. 17 that the radiation between sphere and sphere, cylinder and cylinder is greater than the conduction between them. Therefore the conduction inside the random load can be neglected. Actually the thermal conductivity between contact spheres or cylinders is smaller than the solid phase because of contact thermal resistance. So the ratio will be greater. As the radius *r* and temperature of *Tj* increases, the ratio will increase. As the strain ratio *a* decreases the ratio increases.

As the radius of the sphere or cylinder is less than 1mm the conduction will take main part. That agrees with the results for powder mentioned in the review section.

3.4 Conclusions

Random load pattern related studies are reviewed and analyzed. Two methods are proposed to solve the heat transfer in random load pattern. One is based on the measured results, from which the effective thermal conductivity can be calculated by reverse method. The second one is to treat the random load pattern as orderly arrangement. Radiation and convection are considered, while the conduction is neglected.

CHAPTER 4. CASE STUDIES OF RANDOM LOAD MODEL

In order to validate the random load model, case studies were conducted in two different companies. The calculation results with the random load model were compared with measured data in production.

4.1 Case Study 1 :(CASCO)

The first case study was carried out in Bodycote Thermal Processing plant, Worcester Massachusetts. The workpieces, as seen in Fig. 18, shows that they are small in size and also large in number.

4.1.1 Workpiece data

The workpieces used for the study are shown in Fig. 18 and Table 1.

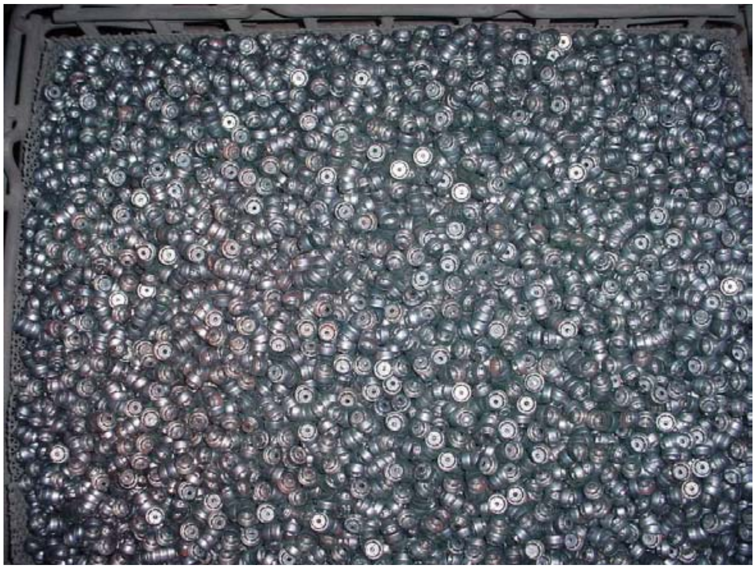


Fig. 18 Casco workpieces

Table 1. Workpiece definition for case 1

Workpiece name:	Casco
Material:	1008 (Carbon Steel)
Weight:	0.0025lbs
Basic shape and size:	Cylinder with diameter 0.7”, thickness 0.13’’, height 0.424”

4.1.2 Furnace data

The furnace is a direct gas fired furnace, as seen in Fig.19. Its data is listed in Table 2. The atmosphere content in this furnace is ammonia. In this furnace there are two chambers, in one chamber the heat treatment process takes place while in other the cooling takes place so there is no loss of time during the heat treatment process.

Fig. 19 Gas fired Furnace

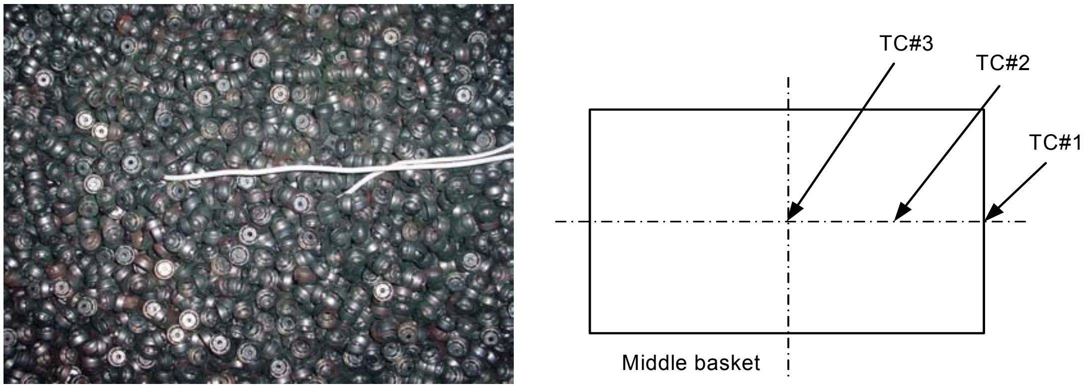
Table 2. Furnace information

Manufacture:	440 Lindure
Total size:	5.1’ X 6’ X 3.5’
Workspace:	36” x 24” x 18”
Heat input:	450,000BTU/hr
Heating elements:	Total weight: 122 lbs
Supports:	15.5 lbs
Roller rails:	43 lbs
Insulation:	Roof Fiber 6”, Brick 9”,
	Side Fiber 6”, Brick 9”,
	Top Fiber 6”, Brick 9”,

4.1.3 Load pattern:

In this case the load is randomly placed in the basket. Three baskets are placed inside the furnace at a time. The load pattern can be seen from Fig.20.The arrangement of the thermal couples is shown in Fig.21

Fig. 20 Load pattern for case 1



(a) (b)

Fig. 21 Arrangement of the thermocouples

Table 3. Load pattern

Each Fixture weight:	120 lbs.
Each Fixture size:	36”x25”x5”
Fixture configuration:	Row 1, Column 1, Layer 3
Parts configuration in each fixture:	Random
Total quantity of workpiece in a single fixture:	10696
Total quantity of workpieces:	32088
Total weight of workpieces in a single fixture:	26.74 lbs
Total weight of workpiece:	80.22 lbs

4.1.4 Processes:

The workpieces are pre-oxidized and are then heated to 1060F and kept at that temperature for about 55 minutes.

4.1.5 Observation and Calculations:

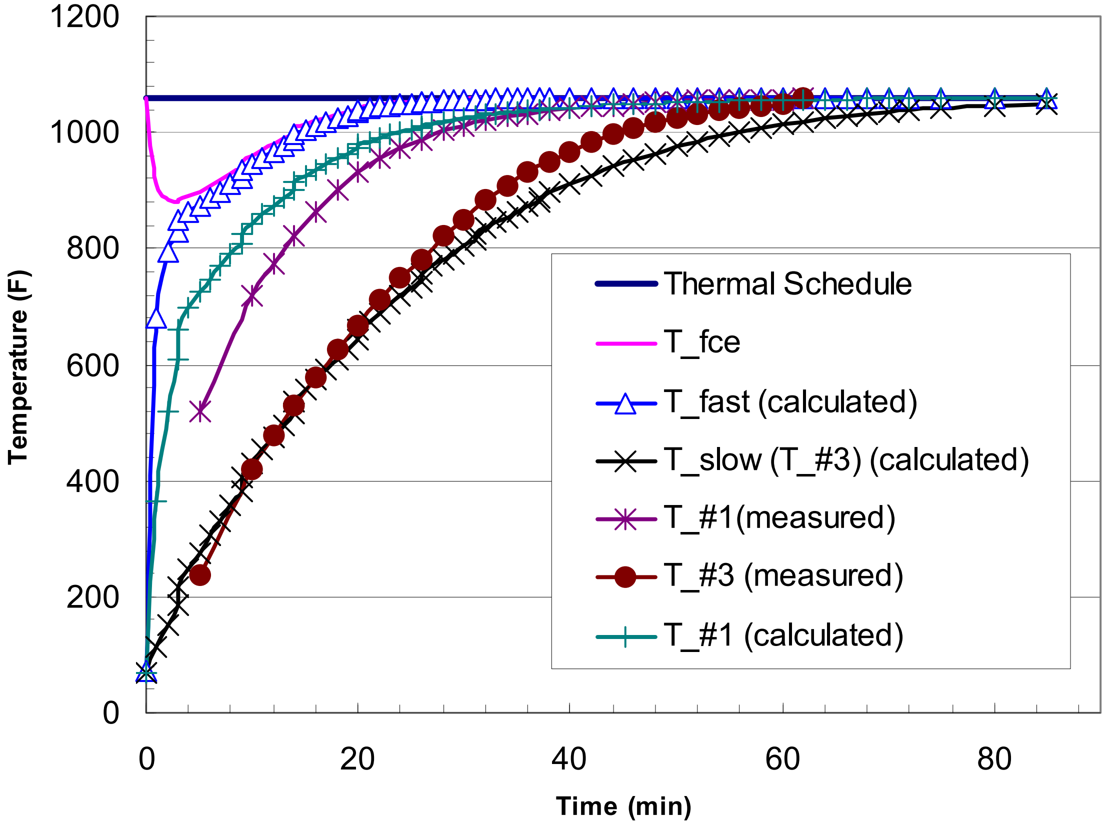


Fig. 22 Comparison of calculated and measured results

In the calculation, although there is no recirculating fan during heat, for the calculation purpose we assume forced convection with a very small flow speed (0.1ft^3/min) was used. The calculated temperature results are shown in Fig. 22.Compared to the measured results at position #1 and position #3 (the slowest heating point, right at the center of the load), it can be seen that they are basically matched. The temperature at fastest heating point is much higher than other points.

4.2 Case Study 2: (UTITEC)

The second case study of random loading was conducted at American Heat Treating Inc. plant at Monroe, CT. There were working on a.410 Stainless steel. The main aim of this case study was to find with the help of CHT-*bf* V 3.0 the time required for the middlemost workpiece to reach the temperature.

4.2.1 <u>Workpiece data</u>

The work pieces of this case study are shown in Fig. 23 and the workpieces details are listed in Table 4 .

Fig. 23 Workpiece

Table 4. Workpiece data

Workpiece Name:	Utitec
Material:	Stainless Steel (410)
Weight:	0.035lbs(each)
Basic shape and size	Ø 0.5” and height 1.65”

4.2.2 Furnace data:

The furnace in which the case study is carried out is a vacuum furnace as seen in Fig. 24

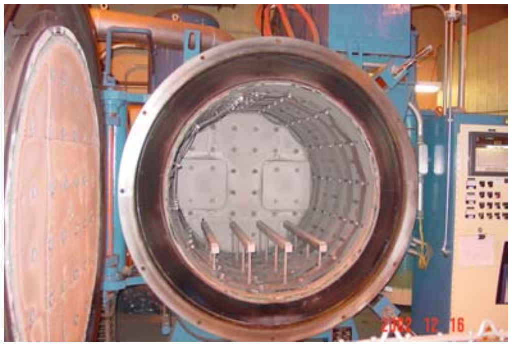


Fig. 24 Vacuum furnace

Table 5. Furnace data

Manufacture:	Vacuum Furnace system
Model:	VFS HL50SEQ2
Total size:	ϕ 6.7'x 5.1'
Workspace:	48" x 24" x 48"
Heat input:	235KVA x 1.7 = 400 KW
Heating elements:	Total weight: 146 lbs
Supports:	40 lbs
Roller rails	150 lbs
Insulation:	Layer1 0.35" graphite, Layer 2 0.9" Kaowool

4.2.4 Load pattern

The workpieces are placed randomly in the fixture as in the following Fig. 25. There were total 5 baskets placed in the furnace at a time .The thermocouple was placed at the centre most point in the middle basket. Thus by placing the thermocouples a comparison can be drawn between the calculated and the measured values.

Fig. 25 Load pattern and arrangement

Table 6. Load pattern

Fixture type (basket/plate)	Basket
Fixture shape (round/rectangular)	Rectangular
Side wall, bottom (solid, net-like)	Net like
Each Fixture weight:	30 lbs
Each Fixture size:	23.5 ” x 14.5” x 6”
Fixture configuration:	Random
Total quantity of workpiece in a single fixture:	8711
Total quantity of workpiece	43555
Total weight of workpiece in a single fixture:	304.5 lbs

4.2.5 *Observation and Conclusion*

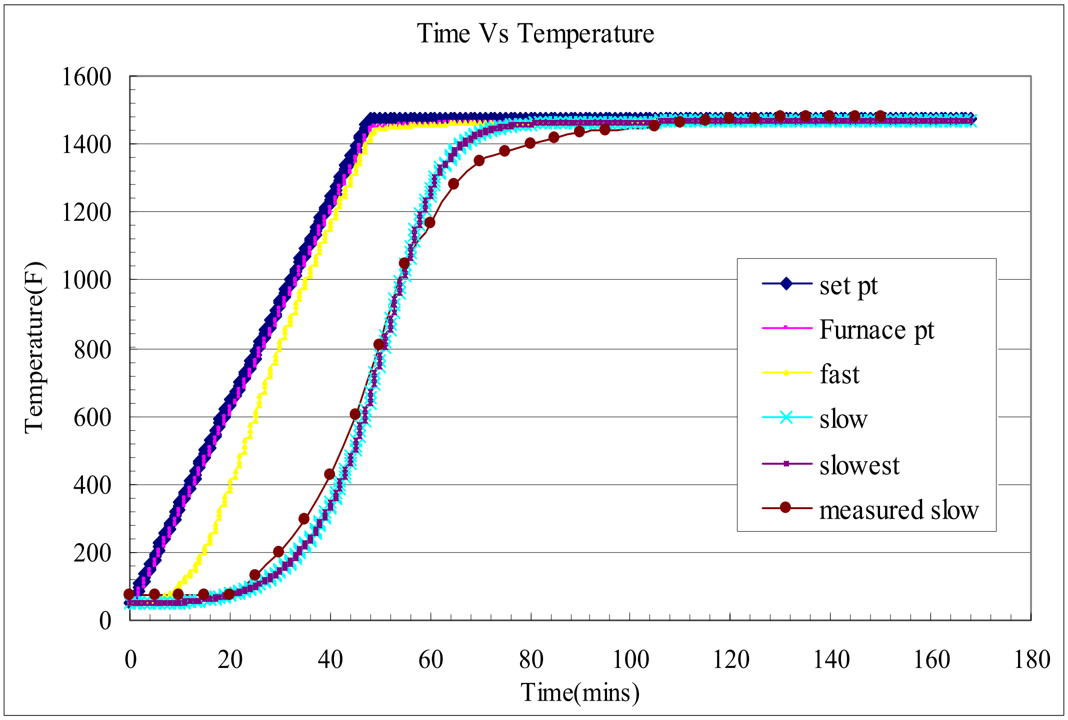


Fig. 26 Graph showing measured and calculated values

It can be observed from the graph that measured slowest and calculated slowest has almost the same trend. There was not much difference between the calculated measured values. The measured and the calculated slowest curve reach 1475 °F in almost the same time. It can be further observed from the graph that the time taken for the calculated slowest part to come to heat is after 75 minutes while the actual measured value comes to heat at around 80 minutes. This shows that there is not much difference in the time calculation between the measured and the calculated values, Thus with the help of the CHT-*bf* system one can effectively find out the time required for the parts to reach the required temperature. This is a very important aspect in determination of the quality of the material. This also helps in calculating the time there by reducing the excessive time required which in turn is directly related to the saving of production cost.

4.3 Conclusion

The case studies will help to validate a relationship between the measured and the calculated values. From the results, it can be seen that the prediction results are very close to the measured data. The first case study was done to check the efficiency of the system while the second case study was done to for the prediction of the load temperature. Thus the system is validated and then used for the predicting the temperature.

CHAPTER 5. CONTINOUS FURNACE MODELING

5.1 Background of Heat Treatment in Continuous Furnaces

Continuous furnaces are widely used for the heat treatment of mass production parts. So to optimize the heat treating process in continuous furnace is of great significance.

A tool for part load design and temperature control in batch furnaces has been developed and put into application under the fund of Center for Heat Treating Excellence. During the former two projects funded by CHTE: 1) Development Of An Analytical Tool For Part Load Design And Temperature Control Within Loaded Furnace And Parts [9-13] and 2) Enhancement Of Computerized Heat Treating Process Planning System (CAHTPS) [14,15], we have visited many member companies of CHTE and investigated the applications of heat treating technology in the United States. In the investigation we also acquired a lot of information on continuous furnaces, which be seen in the former report [1]. Meanwhile the mathematical models for batch furnace are also helpful for the development of module for heat treating processes in continuous furnace. The aim of the development is to achieve a tool for the optimization of load pattern and furnace control including movement and temperature distribution.

5.2 Classification of Continuous Furnaces

Continuous furnaces basically consist of pusher and conveyor furnaces.

1) Pusher furnaces

Pusher furnaces include Skid-Rail furnace and Roller rails furnace. A pusher furnace uses the “tray-on-tray” concept to move workpiece through the furnace. The pusher mechanism pushes a solid row of trays from the charge end until a tray is properly located and proven in position at the discharge end for removal. On a timed basis, the trays are successively moved through the furnace. The cycle time through the furnace is varied only by changing the push intervals. Fig. 27 shows a typical rotary-retort heat treating furnace for continuous carburizing. Because the front end of the furnace must be open to allow continuous charging, sufficient carburizing gas must be fed into the furnace to prevent the admission of outside air. Fig. 28 shows a schematic view of tray movement in a pusher furnace.

2) <u>Conveyor-type Furnaces</u>:

Conveyor-type furnaces include Roller-hearth furnace and Continuous-belt furnace. Roller-hearth furnaces move the workpieces through a heating zone with powered, shaft-mounted rollers that contact the workpieces or trays. Continuous-belt furnaces move the workpieces through mesh or cast-link belts. Conveyors used include woven belts of suitable material, and chains with projecting lugs, pans or trays connected to roller chains. A liquid or gas atmosphere seal is used to maintain atmosphere integrity in the furnace chamber, and fans are used for recirculation the atmosphere.

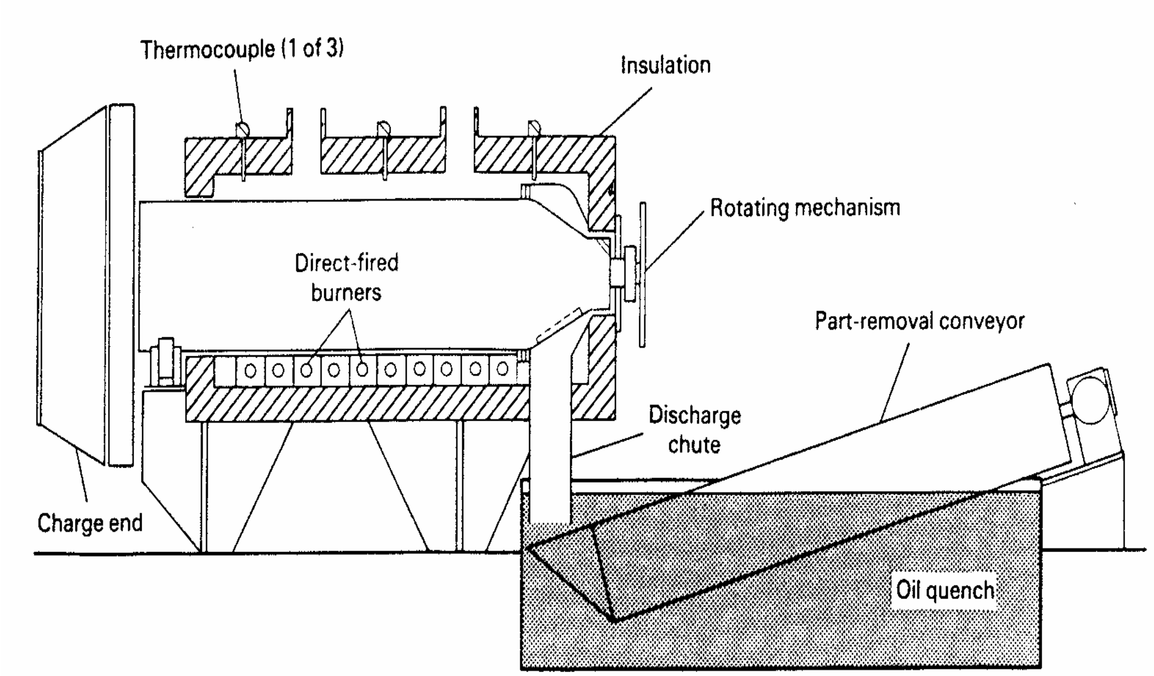


Fig. 27 A rotary-hearth furnace-

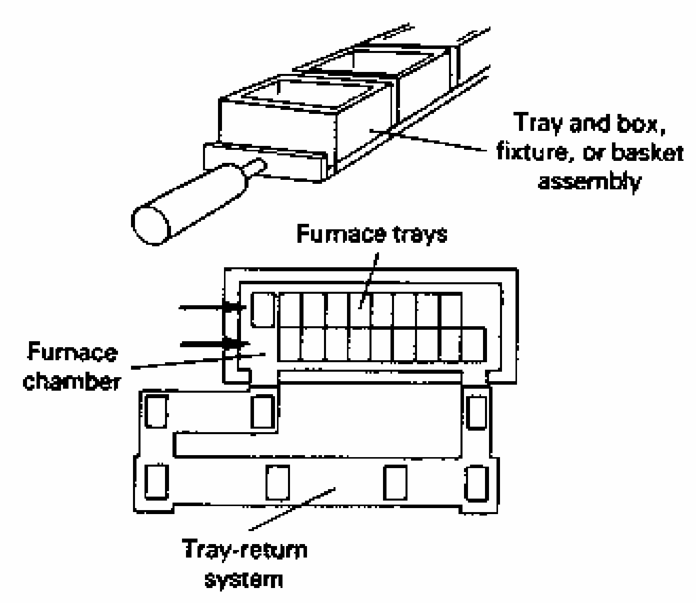
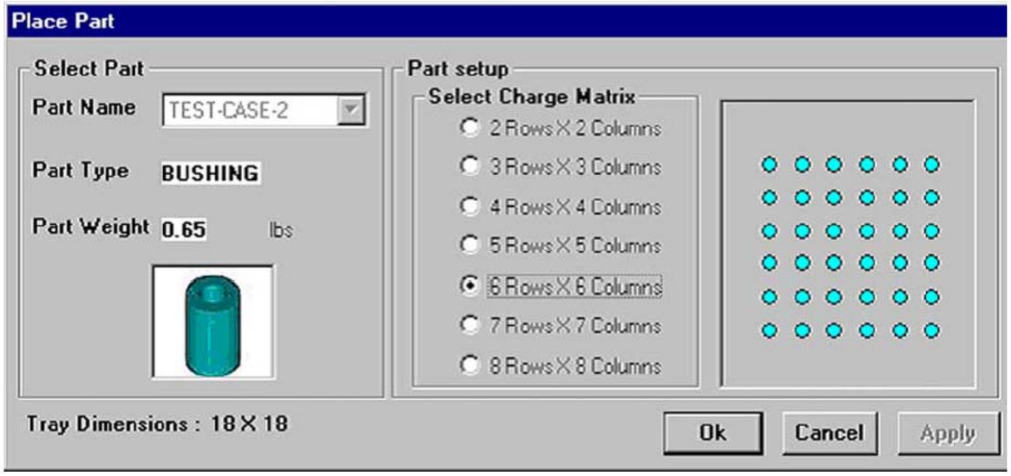


Fig. 28 A schematic view of tray movement in a pusher furnace

5.3 Studies about Continuous Furnaces

There are few software about the optimization of heat treating process in continuous furnace. Among them FurnXpert program is developed to optimize furnace design and operation [16]. It can be used for any type of batch and continuous furnaces. An example for continuous belt furnace for sintering process in powder metallurgy was given. The program mainly focuses on the heat balance of the furnace. The load pattern is just aligned load pattern with just one layer and it cannot deal with the condition of workpieces loaded in the fixtures. While, in this condition the workpieces inside the fixture are heated by adjacent workpieces, not directly by furnace. Fig. 29 shows an interface of load pattern specifications in FurnXpert. The result curves are shown in Fig. 30. In the program it mentioned that finite element method is used for the heat transfer inside the part. However, nothing details about finite element method was presented.

Other software such as ICON and DCON [17] are developed in the mid 1990's. They are just for very simple workpiece shape and based on DOS, so they are not proper for the optimization of heat treating process of arbitrary shape workpieces.



Place Part

Select Part

Part Name: TEST-CASE-2

Part Type: BUSHING

Part Weight: 0.65 lbs

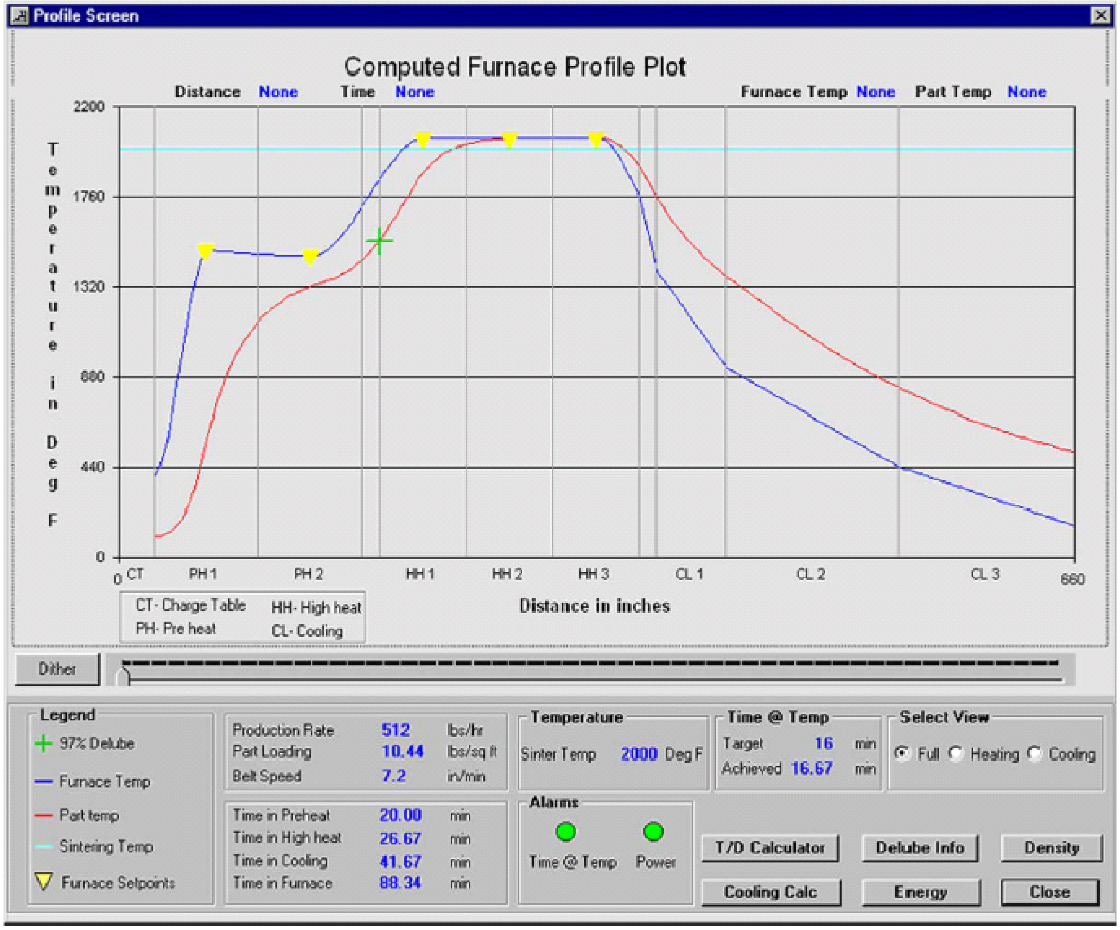
Part setup

Select Charge Matrix

○ 2 Rows X 2 Columns
○ 3 Rows X 3 Columns
○ 4 Rows X 4 Columns
○ 5 Rows X 5 Columns
● 6 Rows X 6 Columns
○ 7 Rows X 7 Columns
○ 8 Rows X 8 Columns

Tray Dimensions : 18 X 18

Fig. 29 The load pattern for continuous belt in FurnXpert software [16]



Profile Screen

Computed Furnace Profile Plot

Distance None Time None Furnace Temp None Part Temp None

Legend

- + 97% Delube
- — Furnace Temp
- — Part temp
- — Sintering Temp
- ▽ Furnace Setpoints

Production Rate	512	lbs/hr
Part Loading	10.44	lbs/sq ft
Belt Speed	7.2	in/min
Time in Preheat	20.00	min
Time in High heat	26.67	min
Time in Cooling	41.67	min
Time in Furnace	88.34	min

Temperature

Sinter Temp 2000 Deg F

Time @ Temp

Target 16 min
Achieved 16.67 min

Select View

● Full ○ Heating ○ Cooling

Alarms

● Time @ Temp ● Power

Fig. 30 The result illustration of FurnXpert software [16]

Some work on numerical simulations is performed for the reheating furnaces in steel making industry [18-20], as shown in Fig. 31, 32 and 33. In this work the movement of workpiece in the furnace is considered. However, the workpieces are usually rods, billets or sheets, of very simple shape. So it is not proper for the actual use in heat treating companies for all kinds of workpieces.

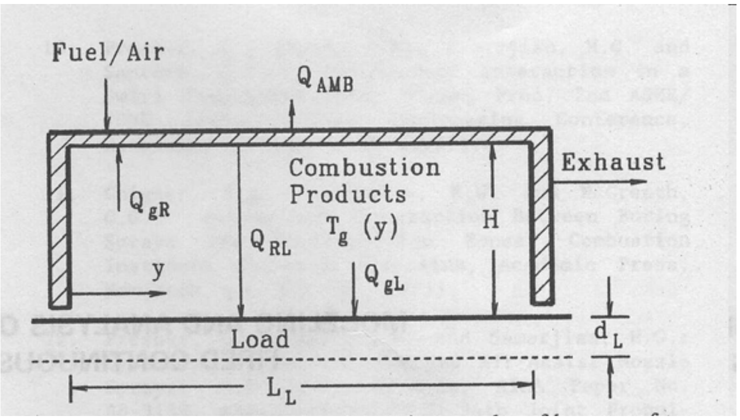


Fig. 31 Schematic showing the various modes of heat transfer in a continuous reheating furnace [18]

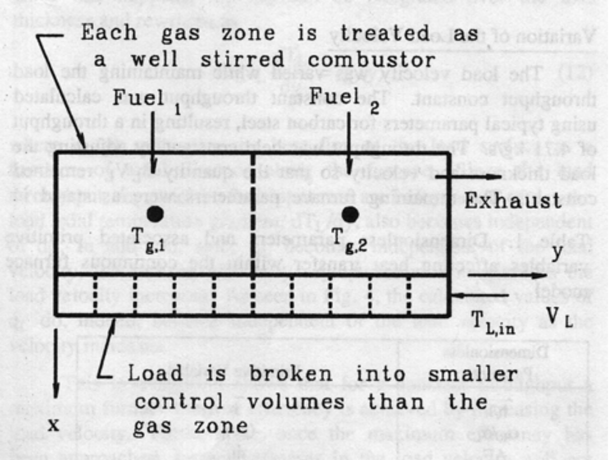


Fig. 32 The individual control volumes used to discretized the one-dimensional continuous heating furnace model [18]

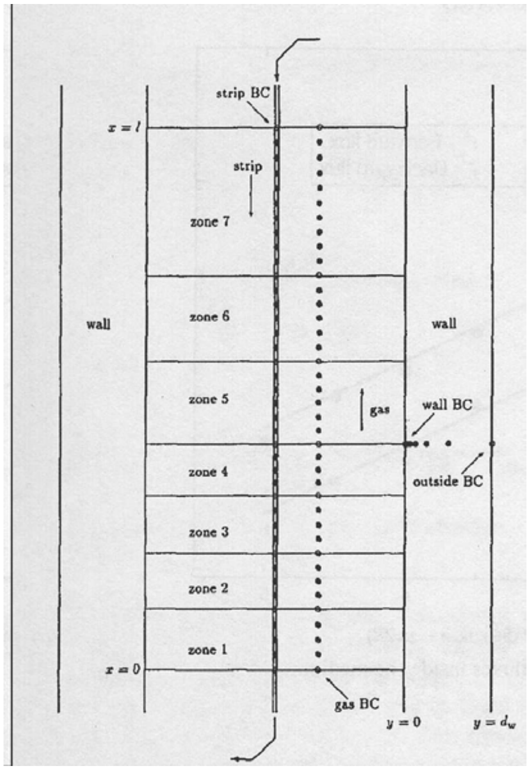


Fig. 33 The heating of strip [19]

5.4. Problem Formulation of Heat Transfer in Continuous Furnace

5.4.1 Comparison of continuous furnace and batch furnace

The comparison of batch furnace and continuous furnace are listed in Table 7 and Table 8. From the comparison the difference and commons are found. Then it provided the base ideas for the continuous furnace model. The heat transfer types are almost the same. The boundary and initial conditions are almost the same. The difference is the calculation domain and the relative furnace temperature to each workpiece during the movement. And for continuous furnace the workpieces are usually smaller than those processed in batch furnace, so the random load pattern seems more important in the calculation.

Table 7. Comparison of continuous furnaces and batch furnaces

	Continuous furnace	Batch furnace
Workpiece	Mass production, small	Size varies greatly, small or middle batch production
Workpiece load pattern	More random load pattern Almost the same for each fixture	More arranged load pattern Maybe different for each fixture
Furnace	More zones Moving bottom Furnace temperature is not uniform along the length direction	One heating zone Stable bottom Furnace temperature is supposed to be uniform
Thermal schedule	T(t)	T(x,t)
PID control	For each zone	One for the whole furnace

Table 8. Comparison of heat transfer in continuous furnaces and batch furnaces

	Continuous furnace	Batch furnace
Conduction inside the workpieces	Same	
Radiation from furnace to workpieces	Furnace temperature is changing with zones	Furnace temperature doesn't change
Convection between furnace and workpieces	Furnace temperature is changing with zones Convection film coefficient changes with the atmosphere and fan condition	Furnace temperature doesn't change Convection film coefficient doesn't change
Radiation from workpiece to workpiece	same	
Conduction between workpieces	same	

5.4.2 <u>Features of continuous furnace</u>:

Through the comparison of batch furnace and continuous furnace, it can be seen that the features of continuous furnace are as follows:

1. For the movement, two types are given, step movement (with basket) and continuous movement (without basket).

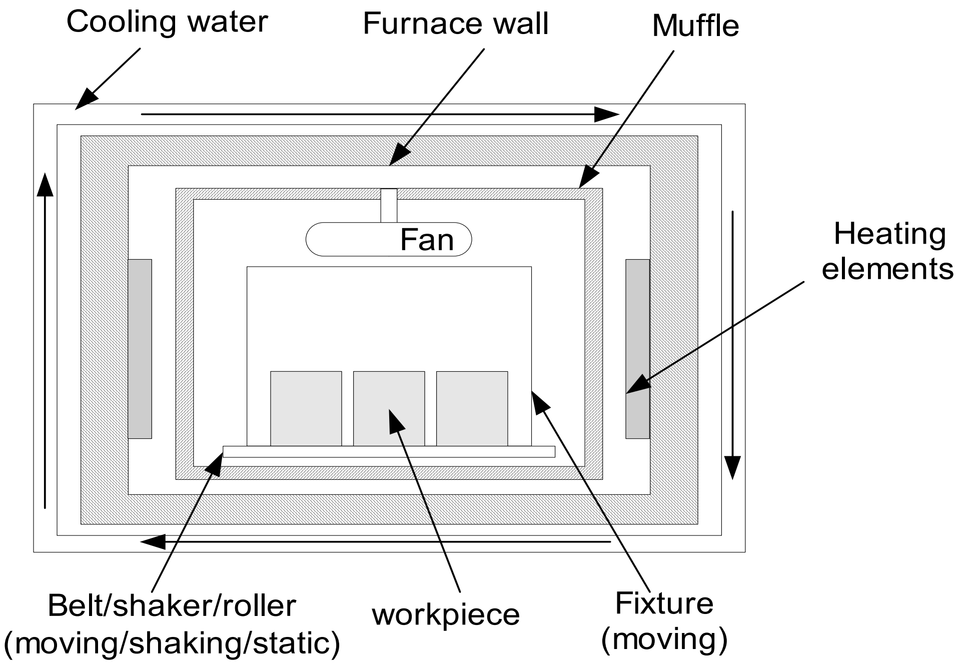
2. The workpiece can be any kind of shape and size, and material.

3. The load pattern considers general packing styles, including random or arranged, rows, columns and layers, distances in each direction of fixture and workpiece as well.

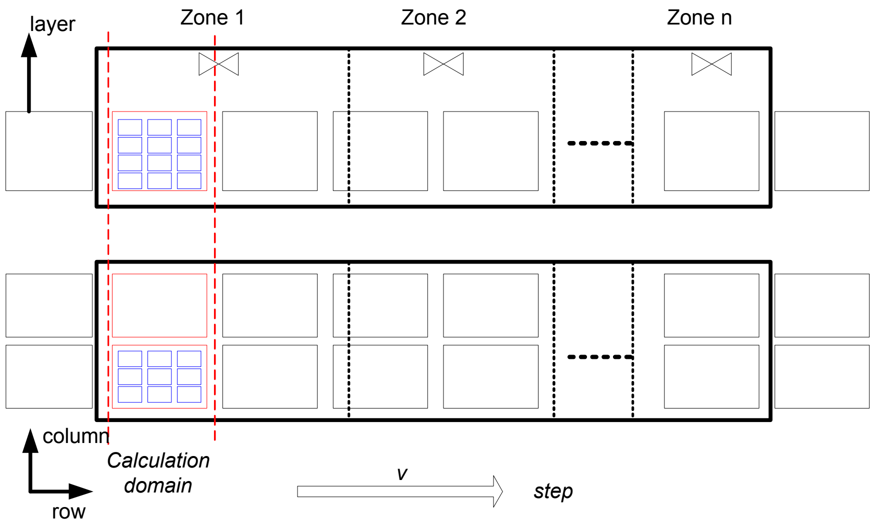
4. Under some conditions the weight of the fixture is far greater than the load. For the basket involved case the movement of the load usually is step by step. While for no

basket involved case the movement of load is usually continuous. For continuous movement usually there is a cycling belt or a shaker.

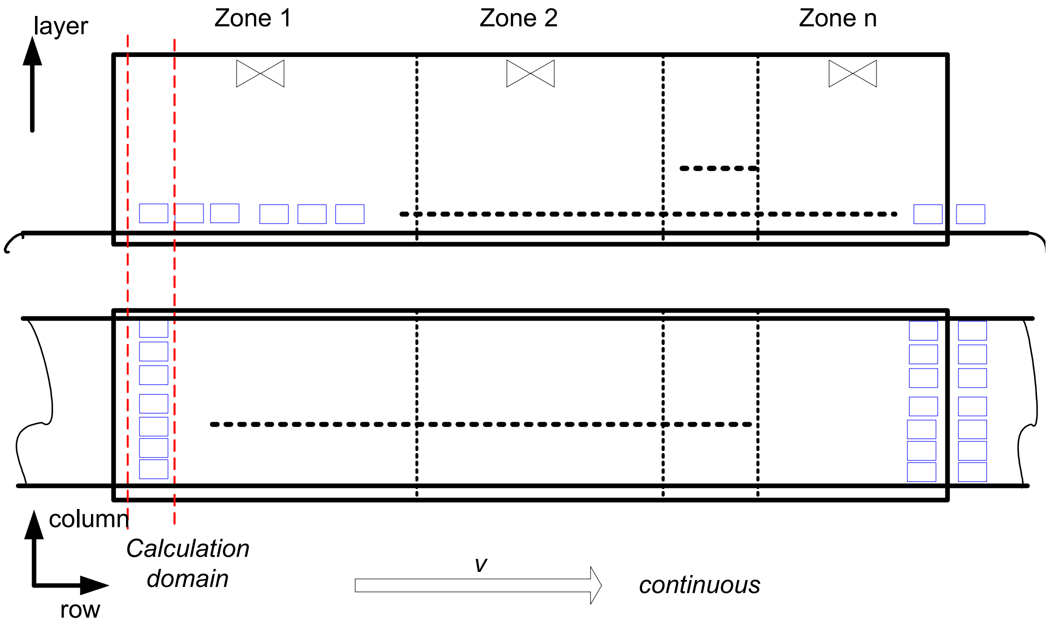
5. Under some conditions there is circulating fan on the roof of each zone.



(a) Section view of furnace structure



(b) Pusher continuous furnace



(c) Conveyor continuous furnace

Fig. 34 Continuous furnace model

5.4.3. Problem definition and assumptions

- The aim of the program is to optimize load speed, load volume and furnace temperature control.
- Assume the furnace temperature doesn’t vary with the load and fixture weight and speed. So the heat balance is just check to see if the furnace power is enough to keep the furnace temperature. The exact furnace temperature drop is not considered. This assumption will simplify the calculation. It means the heat storage in the furnace is not calculated and the furnace structure properties such as weight and thermal properties are not needed. And PID and available heat constants are neither needed.
- No consideration of rotary furnace
- Heat balance in each zone is considered. So the information of furnace structure including furnace wall and accessories is needed.
- The heat transfer between adjacent zones is neglected except between heating zone and cooling zone.
- No round bucket fixture is used in continuous furnace

- There can be no fixture. Fixture is defined here as that directly holds or support workpieces and moves forward with workpieces. Fixture doesn't include belt or conveyor. The recycling belt or conveyors are also considered in the heat balance calculation. They always have the same temperature as the fastest heated workpieces.

5.5. Mathematical Model for Heat Transfer in Continuous Furnace

5.5.1 Selection of calculation domain

There are two kinds of method to deal with the problems related to movement. One is Lagrangian method which focuses on a certain section or position, and the other method is Euler method which traces the movement of one particle or a sample. Here Euler method is adopted.

The selection of the calculation domain should be the maximum load region that repeats the whole process. So for continuous furnace the workpieces are usually directly loaded on the moving belt, so each row of the load in the moving direction will represent the whole load conditions. So just one row of workpieces are taken as the calculation domain. For step by step movement, the workpieces are usually loaded in the fixtures, so in one row of fixture there will be conduction between workpieces or radiation between each other, convection between furnace and workpieces. But there is no radiation directly from the furnace to the inside workpiece. Therefore the center of the load is the last point to reach the soaking temperature. Based on these conditions one row of fixtures are considered as the calculation domain. One fixture in the moving direction for step movement, and one row of workpieces in the moving direction for continuous movement.

5.5.2 Conduction in workpiece

Conduction inside the workpiece is calculated as follows

Because of no 3-D geometrical modeling being used only conduction models for sphere, cylinder and plate are given. Therefore the workpiece have to be classified into these three shapes. For example the cubic can be classified as sphere, bar with rectangle section can be thought as cylinder. For sphere there is conduction in the radial direction only, for cylinder, conduction in radial direction only (no conduction in the axis direction), for plate conduction along the thickness. The differential equations, discretion equations and boundary conditions are shown below.

For sphere, the differential equation is

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c}\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right) \tag{22}$$

Where ρ is density, c is specific heat, r is the radius.

Numerical simulation equation is

$$T_i^{m+1} = T_i^m + \frac{\lambda \cdot \Delta t}{\rho \cdot c}\left(\frac{T_{i+1}^m - 2T_i^m + T_{i-1}^m}{\Delta r^2} + \frac{2}{r}\frac{T_{i+1}^m - T_i^m}{\Delta r}\right) \tag{23}$$

Boundary conditions are

At the surface:

$$\lambda \frac{\partial T}{\partial n} = q_{rad} + q_{conv} \tag{24}$$

where q_{rad} and q_{conv} are the heat rate of radiation and convection, respectively.

At center

$$\lambda \frac{\partial T}{\partial n} = 0 \tag{25}$$

For cylinder, the differential equation is

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{26}$$

Numerical simulation equation is

$$T_i^{m+1} = T_i^m + \frac{\lambda \cdot \Delta t}{\rho \cdot c}\left(\frac{T_{i+1}^m - 2T_i^m + T_{i-1}^m}{\Delta r^2} + \frac{1}{r}\frac{T_{i+1}^m - T_i^m}{\Delta r}\right) \tag{27}$$

For plate, the differential equation is

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c}\frac{\partial^2 T}{\partial x^2} \tag{28}$$

Numerical simulation equation is

$$T_i^{m+1} = T_i^m + \frac{\lambda \cdot \Delta t}{\rho \cdot c}\frac{T_{i+1}^m - 2T_i^m + T_{i-1}^m}{\Delta x^2} \tag{29}$$

The boundary conditions for cylinder and bar are the same as those of sphere.

5.5.3 Radiation inside workpieces and between furnace and workpieces

The radiation between workpiece and workpiece and between furnace and workpiece is calculated also by the same method as present in the before reports. The view factor is calculated under the assumption that the view factor is proportional to the exposed surface area to the total surface area. So how to calculate the distance in row, column and layer is the focus.

For continuous furnace, there is no fixture. So a virtual fixture is assumed there, as shown in Fig. 34 and then the distance of workpieces in row, column and layer can be calculated.

$$d_{row} = L_{vfx}, \qquad d_{col} = \frac{D_{vfx}}{n_{col}}, \qquad d_{lay} = H_{vfx} \tag{30}$$

where d_{row}, d_{col}, d_{lay} are distance between workpieces in row, column and layer directions; n_{row}, n_{col}, n_{lay} are the number of workpieces in row, column and layer directions in each fixture; L_{vfx}, D_{vfx}, H_{vfx} are the length, width and height of the virtual fixture.

For step by step movement, the workpieces are loaded in the fixtures. So the distance can be calculated by the following equations:

$$d_{row} = \frac{L_{fx}}{n_{row}}, \qquad d_{col} = \frac{D_{fx}}{n_{col}}, \qquad d_{lay} = \frac{H_{fx}}{n_{lay}} \tag{31}$$

where L_{fx}, D_{fx}, H_{fx} are the length, width and height of the virtual fixture.

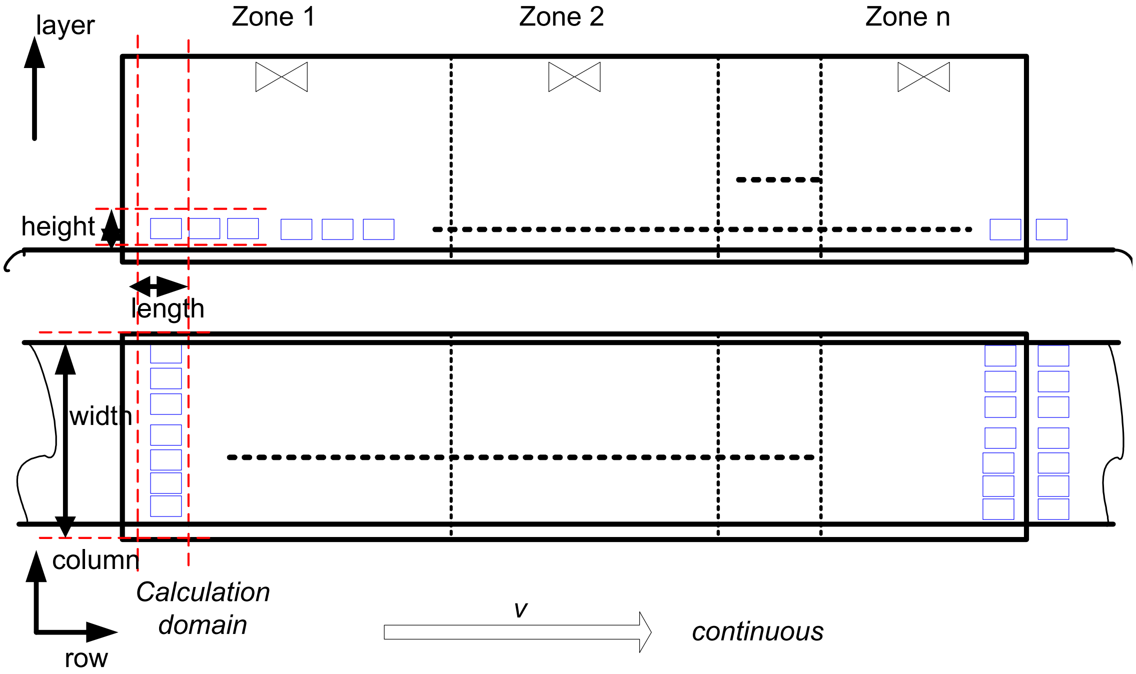


Fig. 35 Virtual fixture size definition for continuous movement

5.5.4 Convection in the furnace

The atmosphere and circulation fan conditions can be different for furnace zones. So the convection film coefficients are calculated for each zone.

In the thermal analysis of workpieces in loaded heat-treating furnace, convection heat transfer is considered as one of the most important boundary condition. The heat energy that enter a workpiece by means of convection heat transfer can be calculated using

$$Q = h \cdot A_S \cdot (T_{flow} - T_S) \tag{32}$$

where h is the heat transfer coefficient; A_S is the surface area of workpiece; T_{flow} and T_S are the temperature of fluid and workpiece surface, respectively. Assuming that the T_{flow} is approximately equal to the furnace temperature, the calculation objective of h will be discussed in this appendix. The average convection heat transfer coefficient, h, is generally calculated by[9]

$$h = \frac{k}{L^*} \cdot Nu_{L*} \tag{33}$$

where k is the thermal conductivity of gas (in $W/m \cdot K$); L^* is the equivalent length of part related to the part geometry and size; and Nu_{L*} is the Nusselt number,

$Nu_{L*} = f\,(Ra, Pr, \textit{Geometric shape}, \textit{boundary conditions})$.

In the calculation the natural and forced convection are considered. And the aligned and staggered load arrangements are also included in the convection film coefficients calculation.

5.6 Numerical Calculations*:*

Based on the heat transfer principle, the following numerical calculation can be formulated for the temperature estimation during the heat treating processes.

5.6.1 Furnace temperature distribution

Take the workpiece as a reference, the furnace temperature involved in the calculation changes with the workpiece row number and time, it can be denoted as follows:

The furnace temperature distribution is the function of temperature zone and transition zone. It is depicted as follows:

$$T_{\_fce}(d) = \begin{cases} T_{\_zonej} + \dfrac{T_{\_zone(j+1)} - T_{\_zonej}}{L_j + L_{j+1}}\left(d - \left(\sum\limits_{i=0}^{j} L_i - L_j\right)\right) & \sum\limits_{i=0}^{j} L_i - L_j \le d \le \sum\limits_{i=0}^{j} L_i + L_{j+1} \\ T_{\_zonej} \quad \sum\limits_{i=0}^{j-1} L_i + L_j < d < \sum\limits_{i=0}^{j} L_i - L_j & \end{cases} \tag{34}$$

where i and j are the zone numbers, d is the distance from the beginning of the furnace, in the range of 0 to the whole length of the furnace; L is the length of furnace zone.

5.6.2 Thermal schedule

The thermal schedule is the target thermal history of workpiece. The thermal schedule for continuous furnace is different from that in batch furnace. In batch furnace the thermal schedule is set before operation as ramp, preheats and soaks. It will not change during heat treating process. But the thermal schedule for continuous furnace varies with the movement speed of the workpieces. If the workpieces moves faster, i.e., the workpieces will stay shorter in each zone, so the total time will become shorter. Finally, the cycle will be shorter. If the movement speed slows down the workpieces will stay longer and the cycle time become longer. Therefore the thermal schedule is determined by the furnace zone temperature and the movement. Equation (34) shows the furnace zone temperatures. By transformation of distance to time by the movement the thermal schedule will be obtained.

The movement is classified into continuous and step by step, thus the transformation of distance to time is also different for these two types of movements. The time for the workpiece to move the distance *d* for continuous movement is

$$t = \frac{d}{V_{con}} \tag{35}$$

where V_{con} is the moving speed of continuous furnace.

Combine the above equation (34) and (35) and then the thermal schedule for continuous movement can be obtained as follows.

$$T_{\_fce}(t) = \begin{cases} T_{\_zonej} + \dfrac{T_{\_zone(j+1)} - T_{\_zonej}}{L_j + L_{j+1}}(V_{con} \cdot t) & \dfrac{\sum_{i=0}^{j} L_i - L_j}{V_{con}} \le t \le \dfrac{\sum_{i=0}^{j} L_i + L_{j+1}}{V_{con}} \\ T_{\_zonej} & \dfrac{\sum_{i=0}^{j-1} L_i + L_j}{V_{con}} < t < \dfrac{\sum_{i=0}^{j} L_i - L_j}{V_{con}} \end{cases} \tag{36}$$

The equation for step by step movement is

$$t = \frac{d}{L_{fx}}(\Delta t_{break} + \frac{L_{fx}}{V_{step}}) \qquad (37)$$

where L_{fx} is the length of the fixture, Δt_{break} is the break time, V_{step} is the instant pushing speed.

Combining equation (34) and (37), the thermal schedule for step by step movement is as follows.

$$T_{\_fce}(t) = \begin{cases} T_{\_zonej} + \dfrac{T_{\_zone(j+1)} - T_{\_zonej}}{L_j + L_{j+1}}\left(\dfrac{L_{fx}}{\Delta t_{break} + \frac{L_{fx}}{V_{step}}} \cdot t\right) & \dfrac{\sum_{i=0}^{j} L_i - L_j}{\frac{L_{fx}}{\Delta t_{break} + \frac{L_{fx}}{V_{step}}}} \le t \le \dfrac{\sum_{i=0}^{j} L_i + L_{j+1}}{\frac{L_{fx}}{\Delta t_{break} + \frac{L_{fx}}{V_{step}}}} \\ T_{\_zonej} & \dfrac{\sum_{i=0}^{j-1} L_i + L_j}{\frac{L_{fx}}{\Delta t_{break} + \frac{L_{fx}}{V_{step}}}} < t < \dfrac{\sum_{i=0}^{j} L_i - L_j}{\frac{L_{fx}}{\Delta t_{break} + \frac{L_{fx}}{V_{step}}}} \end{cases} \qquad (38)$$

Usually it is very fast to push one tray inside the furnace, so the time for pushing can be neglected. Then equation (38) and (39) will be as follows, respectively.

$$t = \frac{d}{L_{fx}}\Delta t_{break} \qquad (39)$$

$$T_{\_fce}(t) = \begin{cases} T_{\_zonej} + \dfrac{T_{\_zone(j+1)} - T_{\_zonej}}{L_j + L_{j+1}}\left(\dfrac{L_{fx}}{\Delta t_{break}} \cdot t\right) & \dfrac{\sum_{i=0}^{j} L_i - L_j}{\frac{L_{fx}}{\Delta t_{break}}} \le t \le \dfrac{\sum_{i=0}^{j} L_i + L_{j+1}}{\frac{L_{fx}}{\Delta t_{break}}} \\ T_{\_zonej} & \dfrac{\sum_{i=0}^{j-1} L_i + L_j}{\frac{L_{fx}}{\Delta t_{break}}} < t < \dfrac{\sum_{i=0}^{j} L_i - L_j}{\frac{L_{fx}}{\Delta t_{break}}} \end{cases} \qquad (40)$$

From equation (34), (36), (38) and (40) it can be seen that the furnace temperature is not only the function of furnace length, but also the function of time, i.e., the workpiece is fixed and the furnace is moving. The relative movement between furnace and workpiece make the thermal schedule.

For continuous movement the thermal schedule is the same kind of shape as the furnace temperature distribution, just with the distance axis changed to time axis. But for step by step movement the workpieces are load in fixture. Thus, the temperature change of the workpiece located at the fixture center is taken to represent the thermal schedule of the calculation domain. The transformation of temperature-distance curve to temperature – time curve for step by step movement is shown in Fig. 36 calculated by equation (38) or (40).

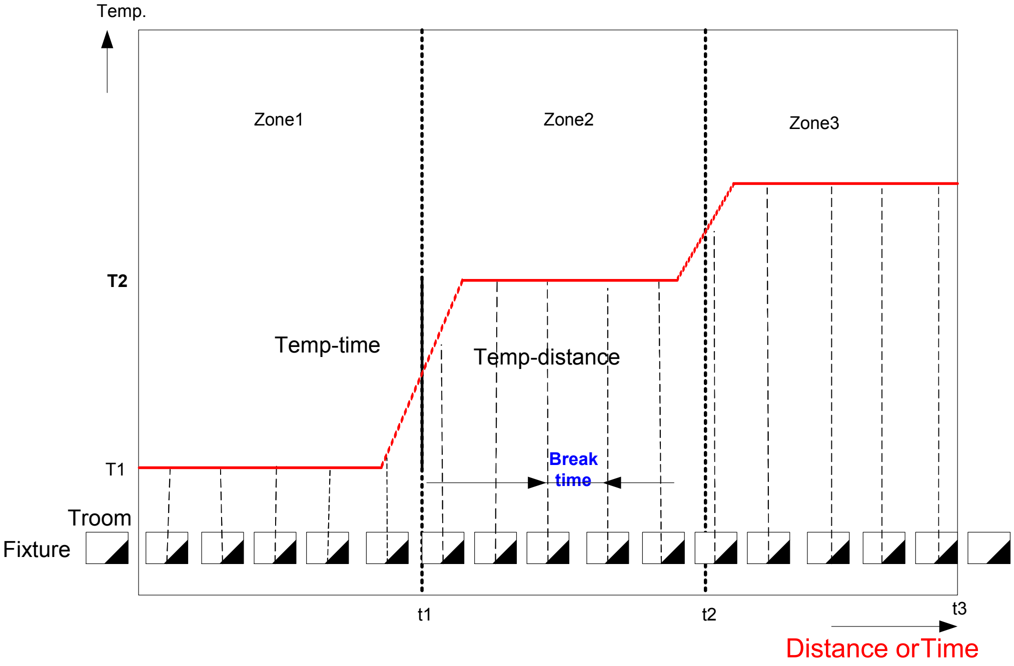


Fig. 36 Relationship between temperature-time curve and temperature-distance curve for step by step movement

5.7 Furnace Temperature & Heat Balance

The heat transfers in the adjacent zones of the continuous furnace are shown in Fig. 37.

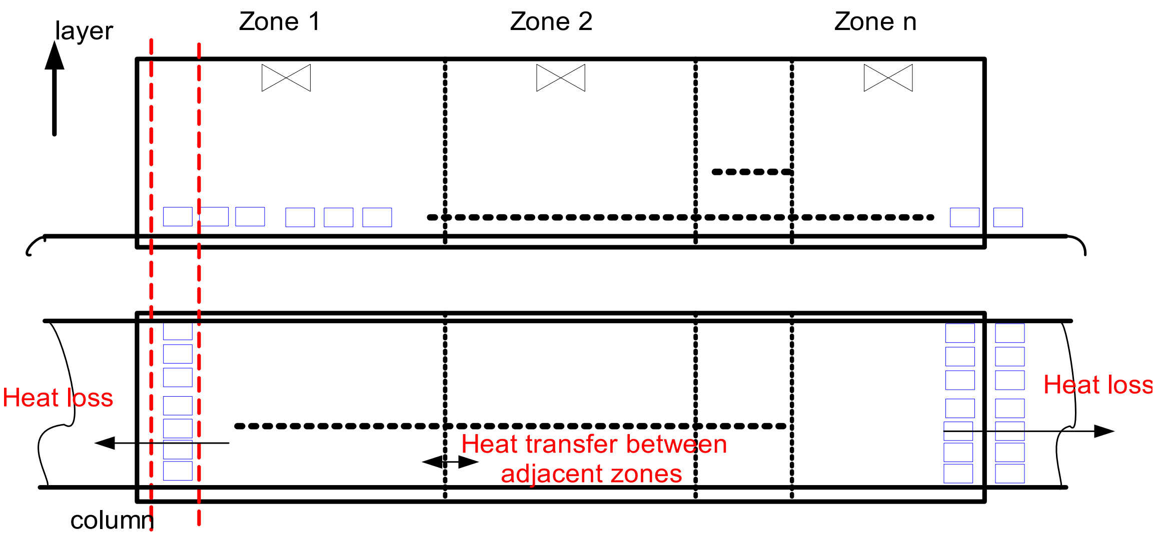


Fig. 37 Heat loss terms

(1) Heat balance in each zone:

The calculation deals with static condition. Therefore the heat balance is dynamic. Assume furnace temperature doesn't change with load variation. So the heat storage in the furnace is not necessary to be included. 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.

The dynamic heat balance is

$$Q_{input\_p} + Q_{fan\_p} = Q_{load\_p} + Q_{fix\_p} + Q_{belt\_p} + Q_{wall\_loss\_p} + Q_{zone\_p} + Q_{shell\_cooling\_p} \quad (41)$$

where

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

$$Q_{input\_p} = Q_{load\_p} + Q_{fix\_p} + Q_{belt\_p} + Q_{wall\_loss\_p} + Q_{zone\_p} + Q_{shell\_cooling\_p} - Q_{fan\_p} \quad (42)$$

It is compared with the power of the furnace to see if it exceeds the power, which means the heat balance cannot be kept. 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. The procedure is initial furnace temperature- load temperature and all heat terms judge if the heat balance can be kept. If it cannot be kept the calculation will give warning and stop calculation, otherwise the calculation continues with the furnace temperature not changed.

These heat terms are the functions of furnace temperature. Adjust the furnace temperature to keep the heat balance. The heat input should also be calculated directly by the connected heat input and the available heat coefficient.

(2) <u>Heat terms</u>:

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*.

1) Heat absorbed by the load Q_{load_p}*:*

$$Q_{load\_p} = C_{load\_p} \sum_i \sum_j \sum_k (\rho g c)_{wp} (T^{m+1}_{i,j,k} - T^{m}_{i,j,k}) \quad (43)$$

where C_{load_p} is the ratio of load held in each zone over the calculation domain; the total of ijk is just for the calculation domain, not the whole furnace zone.

2) Heat absorbed by fixture Q_{fix_p}:

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

$$Q_{fix\_p} = (w\ c)_{fix}(T_{fix}^{m+1} - T_{fix}^{m}) \tag{44}$$

Here assume the fixture temperature is uniform in each zone and takes the same temperature of the fastest heated workpiece.

3) Heat absorbed by moving belt or conveyor Q_{belt_p}:

$$Q_{belt\_p} = L_p(wc)_{belt}(T_{belt}^{m+1} - T_{belt}^{m}) \tag{45}$$

Where w is the weight of belt unit length.

Here assume the belt temperature is uniform in each zone and takes the same temperature of the fastest heated workpiece.

4) Heat loss from furnace wall $Q_{wall\_loss\_p}$**:**

$$Q_{loss\_p} = 2(L_pW_p + L_pH_p + H_pW_p)\frac{T_{fce\_p} - T_{room}}{t_1/k_1 + t_2/k_2 + 1/\alpha} \tag{46}$$

Where T_g and T_a are the temperature of furnace gas in furnace and out of furnace; 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; α is the thermal diffusivity from furnace outside to atmosphere.

5) Heat absorption by furnace shell cooling water $Q_{shell\_cooling\_p}$**:**

$$Q_{shell-cooling\_p} = (\rho gc)_{water}v\Delta t(T_{out} - T_{in}) \tag{47}$$

where v is flowing rate.

6) Heat transfer between adjacent zones and heat loss from ends Q_{zone_p}**:**

$$Q_{zone\_p} \tag{48}$$

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.

7) Heat release by circulation fan Q_{fan_p}**:**

$$Q_{fan\_p} = HP_{fan} \cdot \left(\frac{520}{460 + T_{\_fce}} \right) \Delta t \tag{49}$$

where HP_{fan} is the power of the fan. The same equation provided by Surface Combustion.

8) Heat input by the furnace Q_{fce_p} **:**

$$Q_{fce\_p} = K_{AH} \cdot q_{conn} \Delta t \tag{50}$$

5.8 Random Load Pattern

For random load pattern, it is limited to the load in the fixtures in the step by step movement. There are two methods to calculate the heat transfer in the random load pattern, the same as mentioned in the before reports [14]. The first method is the effective thermal conductivity method, in which the effective thermal conductivity is first calculated by experiment and inverse method and then is used to actual load. The second method is the method based on the assumption of arranged load pattern. As the random load pattern is assumed to be arranged together, then heat transfer can be calculated by the method for arranged load pattern.

5.9 Output Results and Optimization of Furnace Control

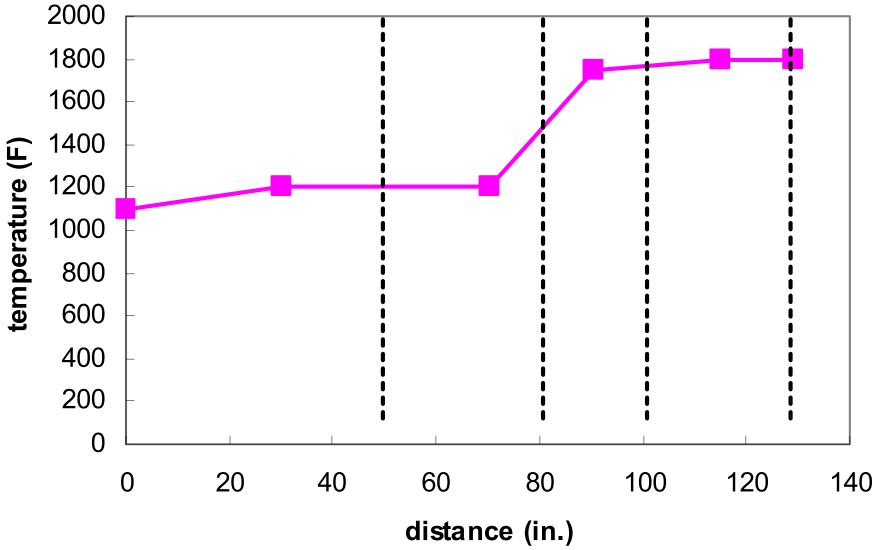
5.9.1 Output results

As the calculation is finished, the following results are provided:

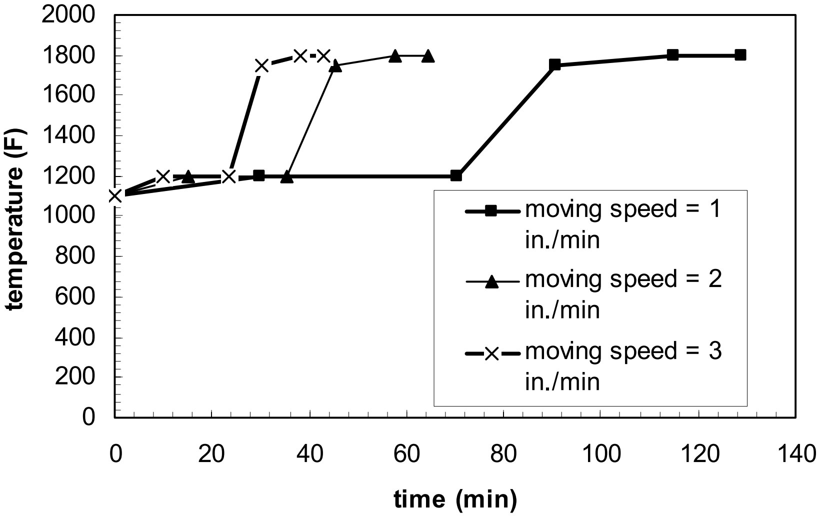
- Temperature vs. time curves of each part in the calculation domain The temperature of every workpiece in the calculation domain is calculated and output into text files. The temperature of critical workpieces such as the fastest heated and slowest heated workpieces can be directly plotted out after calculation.
- The heat absorption rate of the calculated domain is calculated.

5.9.2 Optimization of furnace control

The aim of the system is to optimize the furnace control and then improve efficiency, decrease cycle time and slash cost. The furnace control includes the movement of the furnace and furnace temperature distribution. The moving speed will decide the soaking time in each zone. And furnace zone temperatures are the same as the preheat temperatures in the batch furnace. Therefore both of the moving speed and the furnace temperature determine the thermal schedule. So to optimize the heat treatment in continuous furnace is to optimize the moving speed, furnace zone temperature distributions and part load pattern. Here one example shows how the moving speed affects the thermal schedule. It can be seen from the graph that increasing the moving speed the thermal schedule becomes shorter; the stay time of workpieces in each zone becomes shorter. Then the workpiece at the load center perhaps can not reach the required temperature. It the speed is very slow, then the cycle time will be too long and it leads to the decrease of efficiency.



(a) Furnace zone temperature distribution



(b) Thermal schedule under different moving speed

Fig.38.The effects of moving speed on thermal schedule of continuous furnace

5.10 Summary

Research was done to study various types of continuous furnaces used in the heat treatment plants .The basics aim of studying these furnaces were to find a mathematical model to achieve a tool for the optimization of load pattern and furnace control including movement and temperature distribution. The various heat terms that were involved in calculation of the furnace temperature were studied. Studies were done to calculate the change in the temperature distribution of the load pattern with the movement.. Mathematical model was developed to calculate the variation of the load pattern with the variation in the movement of the load pattern.

CHAPTER 6. SYSTEM DESIGN

6.1 System Structure

Based on the heat transfer calculation principle for continuous furnace Chapter 5, a database based computer-aided heat treat planning system for continuous furnace has been developed. The system consists of five modules: workpiece definition module, continuous furnace module, part load definition module, database management module and the system configuration module. Fig.39 Tells what a user can do in our system from the user's perspective. The sequence chart for the system is illustrated in Fig.40. It explains the logic sequence for a user to do a complete case. Fig. 41 is the formal flowchart for our system. It follows the steps of workpiece definition, continuous furnace definition, continuous furnace control, and load pattern definition. The last step is calculation and results analysis. The workpiece, material, continuous furnace and atmosphere databases are the foundation of the module.

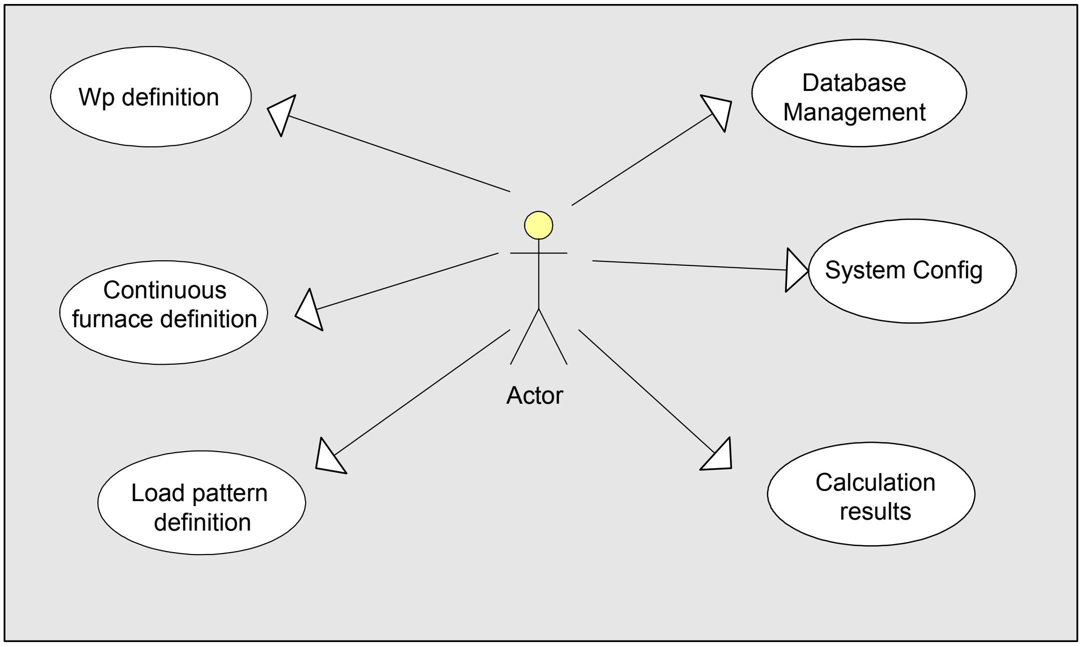


Fig. 39 Users perspective for CHT-*cf*

The Fig. 40 shows the sequence chart for the CHT-*cf* system and the user system interaction at various levels. The figure also shows the dependencies between the various models and the data required before proceeding further to the next level. Also the ability for the user to go back and reconfigure the data after obtaining the results is shown in steps 5 and 6 in Fig. 40. This is a brief view for the user - software interaction and a flow chart for this model is also shown in Fig. 41.

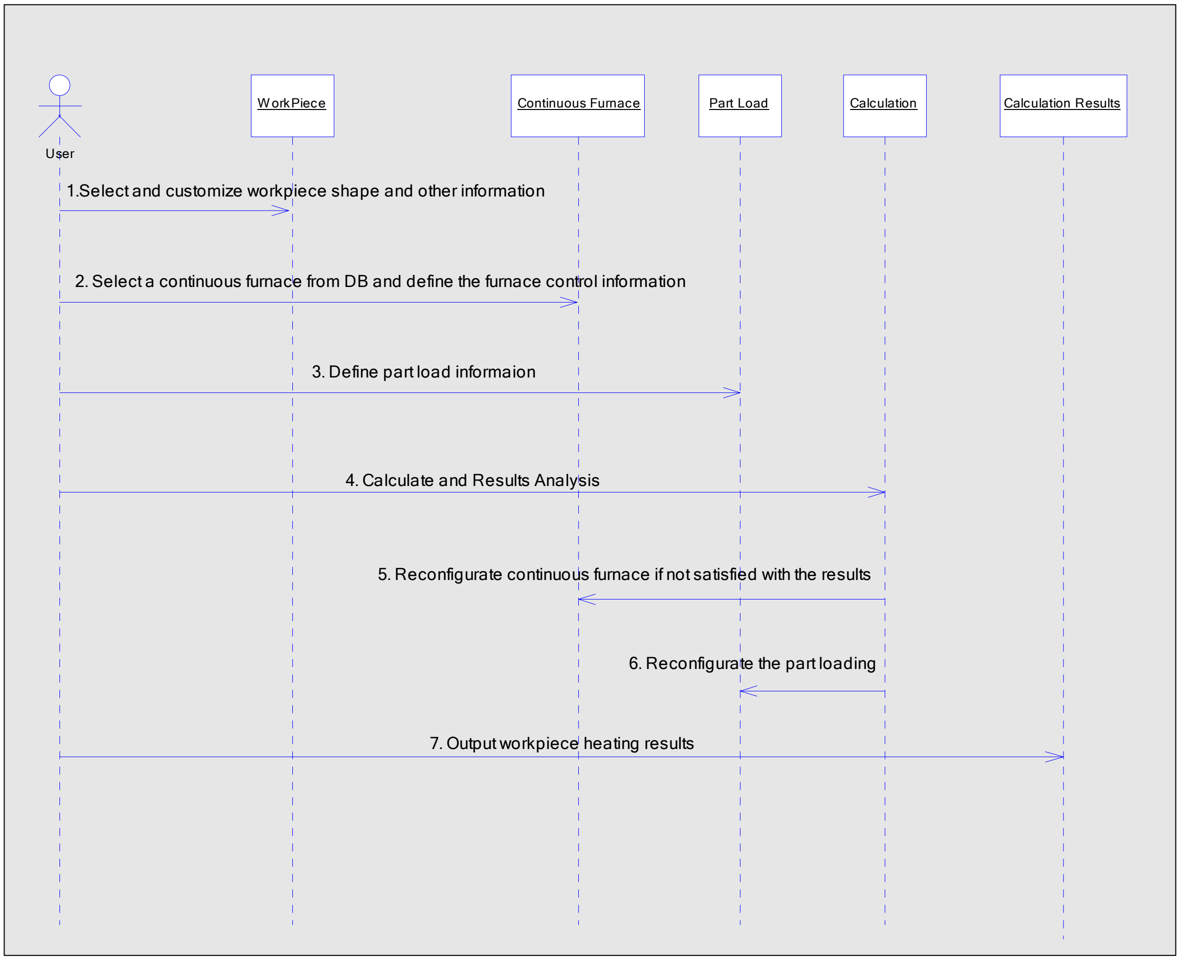


Fig. 40 Sequence chart for CHT-*cf*

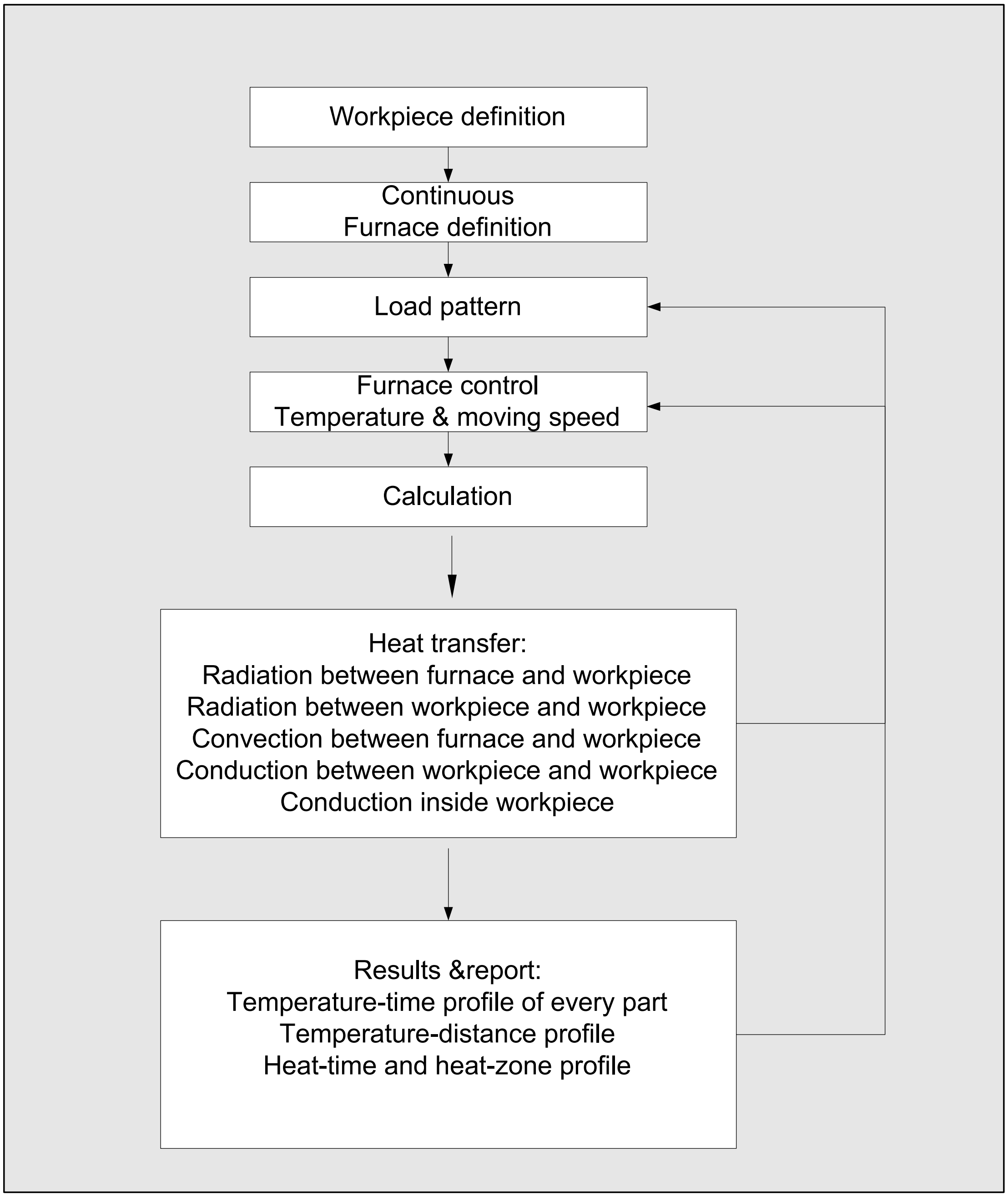


Fig. 41 Flowchart for continuous furnace

The CHT-*cf* system is consists of several modules. The final system is integrated closely with several user interfaces that tie those modules. The system architecture is shown in Fig. 42. The main modules consist of Workpiece definition, Furnace Configuration, Part load design and Calculation and results. There are three more independent modules apart from the main modules. These modules are Database management, System Configuration and User account configuration. They are used for configuring the support systems like databases; user accounts etc., Apart from these modules an independent Microsoft Access Database is also present to support the software. The main modules access the data from this database during the calculations and the database is managed by the Database Management module.

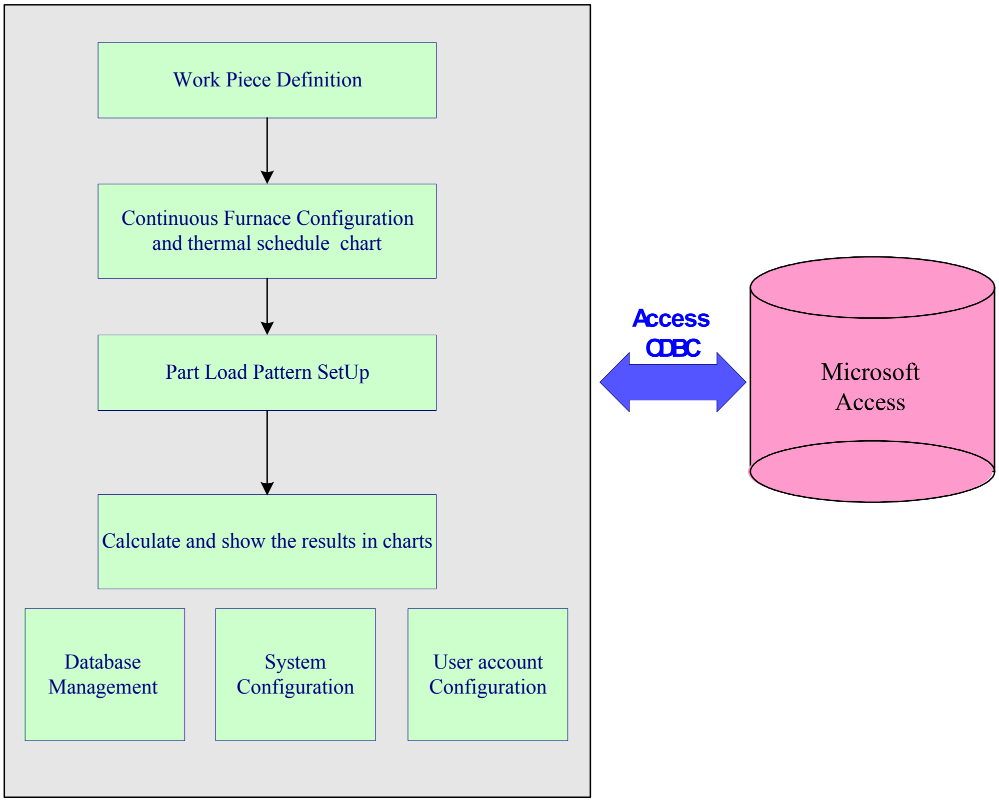


Fig. 42 System architecture

6.2 Database Design for Continuous Furnaces

The database is the foundation of the system. Databases such as material, atmosphere and fuel are the same as those for batch furnace. But the continuous furnace is different from batch furnace, so the continuous furnace database is constructed. Fig.43 is the structure of continuous furnace. It mainly includes the image path, type and zone information such as length, temperature, horsepower of recirculation fan, atmosphere and etc. At most 10 zones are permitted in the database.

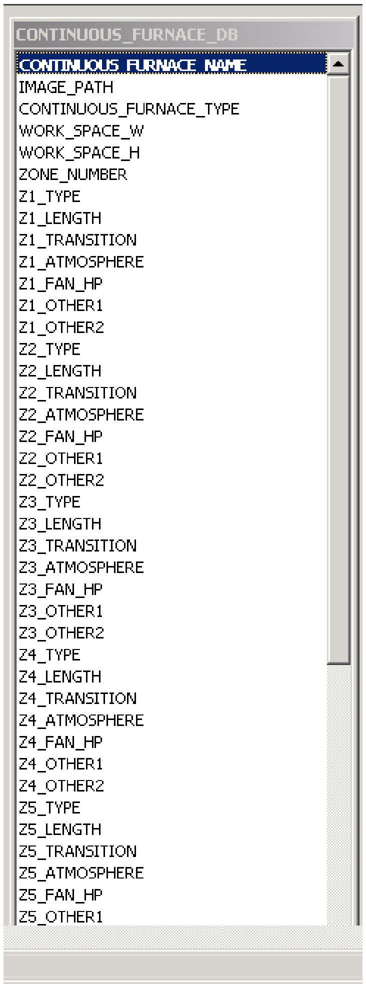
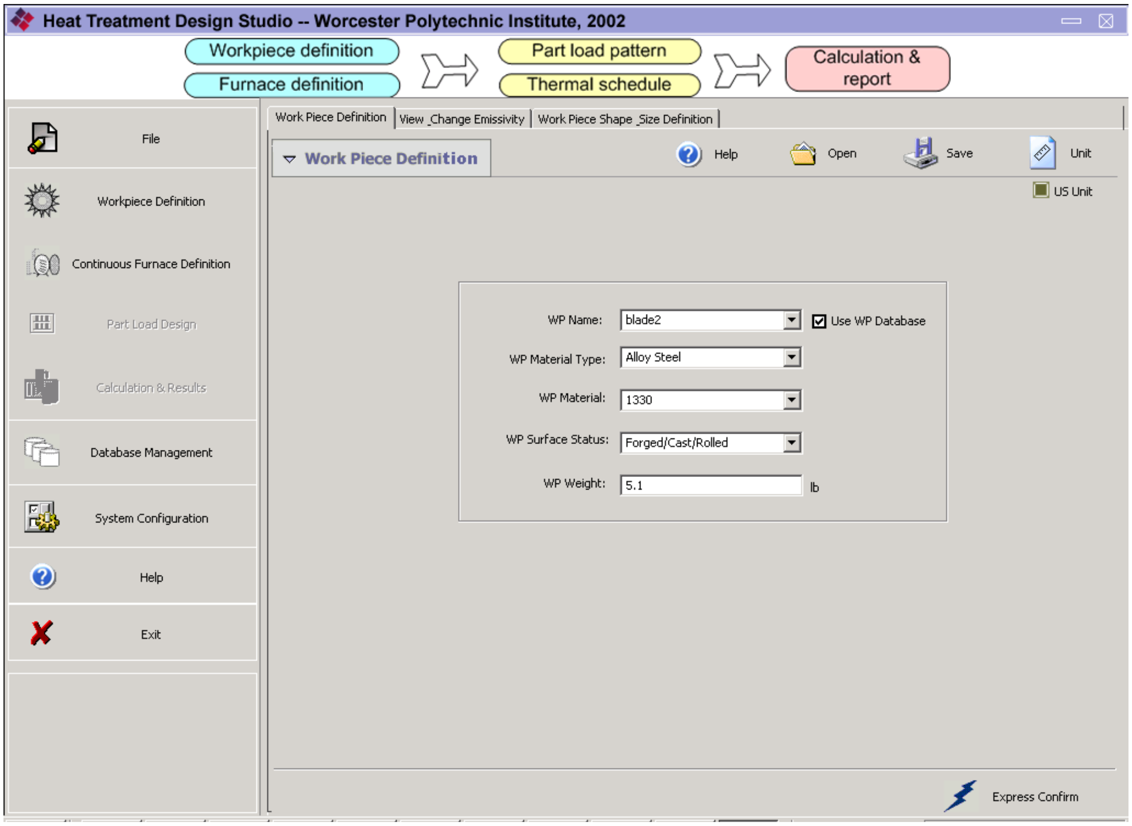

CONTINUOUS_FURNACE_DB
CONTINUOUS FURNACE NAME
IMAGE_PATH
CONTINUOUS_FURNACE_TYPE
WORK_SPACE_W
WORK_SPACE_H
ZONE_NUMBER
Z1_TYPE
Z1_LENGTH
Z1_TRANSITION
Z1_ATMOSPHERE
Z1_FAN_HP
Z1_OTHER1
Z1_OTHER2
Z2_TYPE
Z2_LENGTH
Z2_TRANSITION
Z2_ATMOSPHERE
Z2_FAN_HP
Z2_OTHER1
Z2_OTHER2
Z3_TYPE
Z3_LENGTH
Z3_TRANSITION
Z3_ATMOSPHERE
Z3_FAN_HP
Z3_OTHER1
Z3_OTHER2
Z4_TYPE
Z4_LENGTH
Z4_TRANSITION
Z4_ATMOSPHERE
Z4_FAN_HP
Z4_OTHER1
Z4_OTHER2
Z5_TYPE
Z5_LENGTH
Z5_TRANSITION
Z5_ATMOSPHERE
Z5_FAN_HP
Z5_OTHER1

Fig. 43 Continuous furnace database structure

6.3. System Interface Design

6.3.1 Workpiece Definition

Workpiece definition includes workpiece material, surface status, weight, surface condition, emmisivity, shape and size. These definitions are shown in Figs.44 - 46.



Heat Treatment Design Studio -- Worcester Polytechnic Institute, 2002

WP Name: blade2

☑ Use WP Database

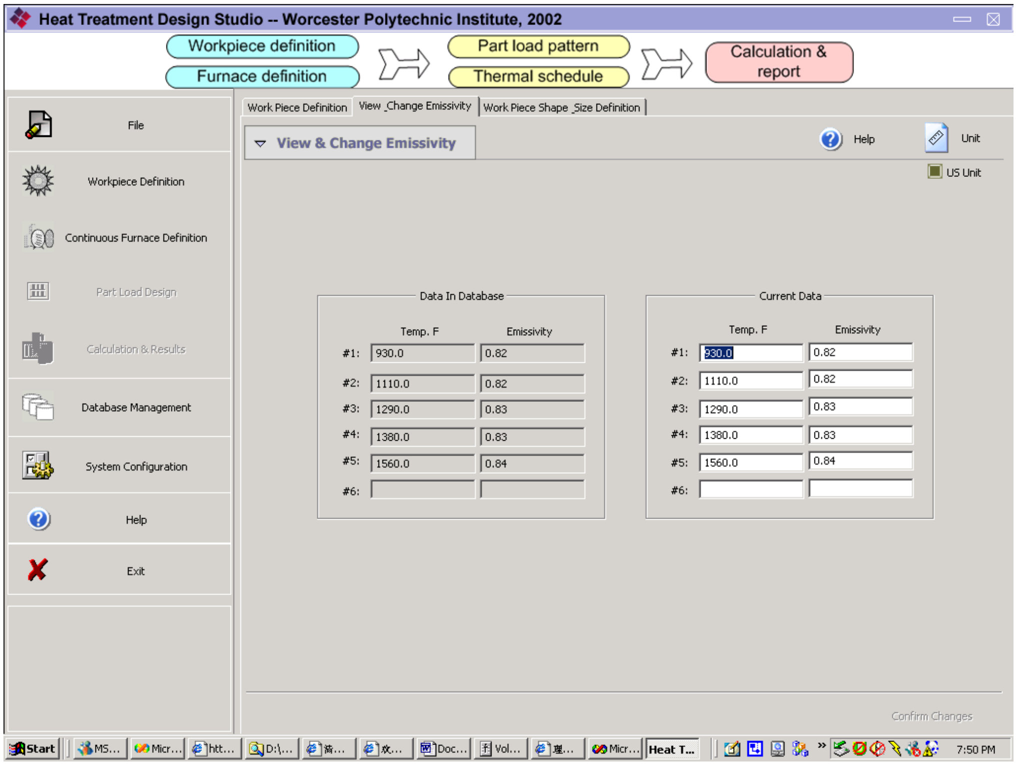
WP Material Type: Alloy Steel

WP Material: 1330

WP Surface Status: Forged/Cast/Rolled

WP Weight: 5.1 lb

Fig. 44 Workpiece definition 1



☑ US Unit

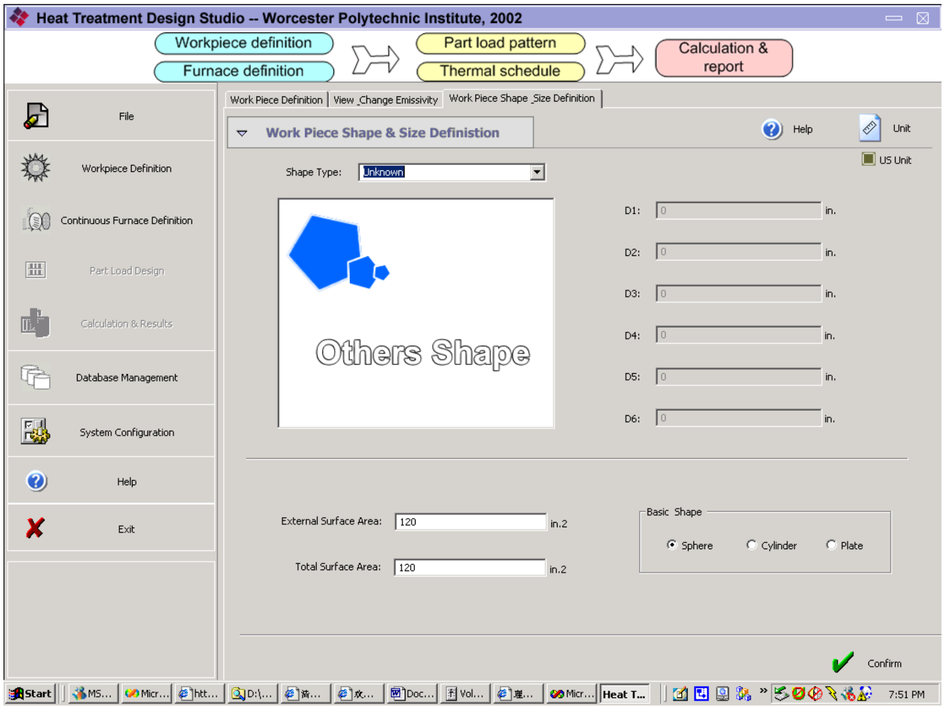
Data In Database

	Temp. F	Emissivity
#1:	930.0	0.82
#2:	1110.0	0.82
#3:	1290.0	0.83
#4:	1380.0	0.83
#5:	1560.0	0.84
#6:		

Current Data

	Temp. F	Emissivity
#1:	930.0	0.82
#2:	1110.0	0.82
#3:	1290.0	0.83
#4:	1380.0	0.83
#5:	1560.0	0.84
#6:		

Fig. 45 Workpiece definition 2



☑ US Unit

Shape Type: Unknown

D1: 0 in.
D2: 0 in.
D3: 0 in.
D4: 0 in.
D5: 0 in.
D6: 0 in.

External Surface Area: 120 in.2
Total Surface Area: 120 in.2

Basic Shape: ● Sphere ○ Cylinder ○ Plate

Fig. 46 Workpiece definition 3

6.3.2 Furnace Definition

Furnace definition contains four pages. The type of furnace used is selected in the first page and the number of zones and its corresponding temperatures are defined. This section also includes the input of the virtual fixture data .The zone length and height are specified along with the temperature The interface for Continuous furnace definition containing four pages is shown in Fig.48 – 51.

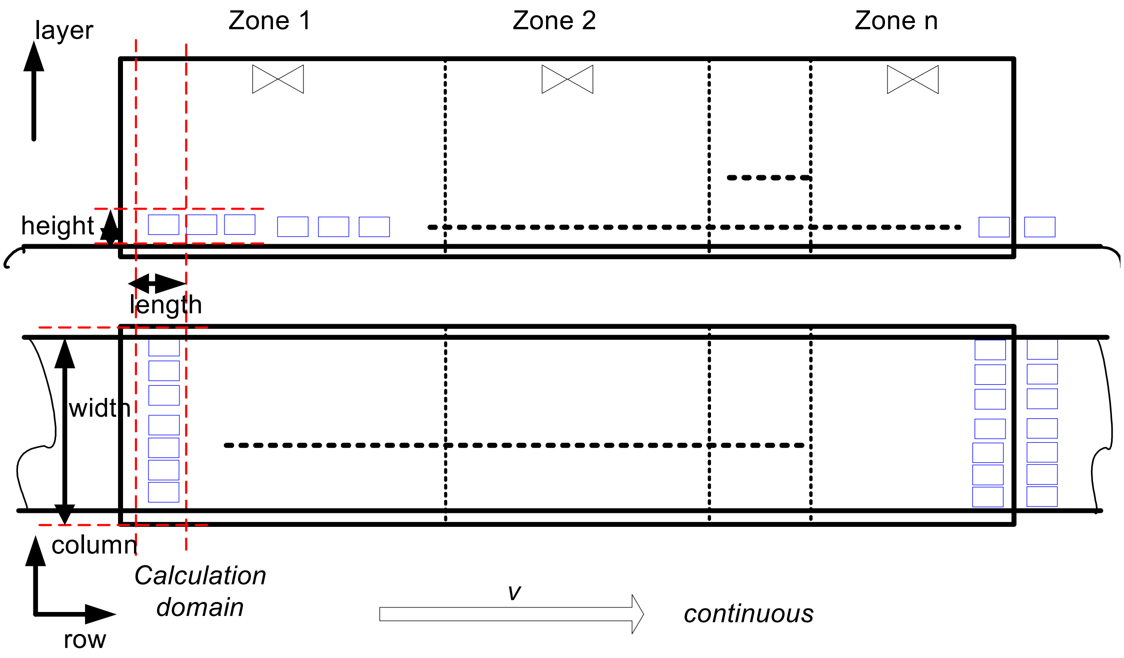
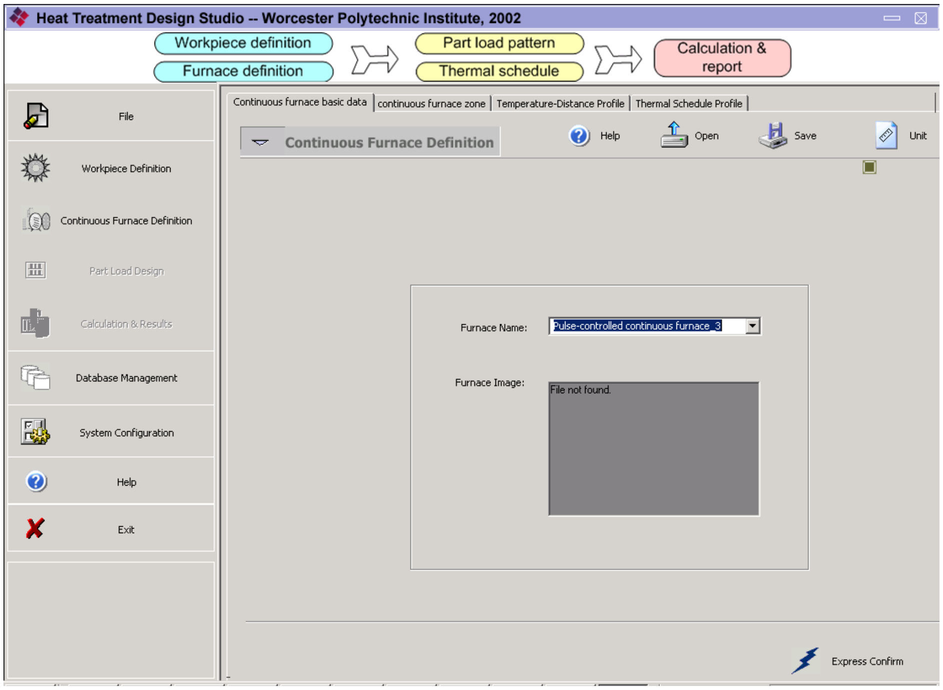


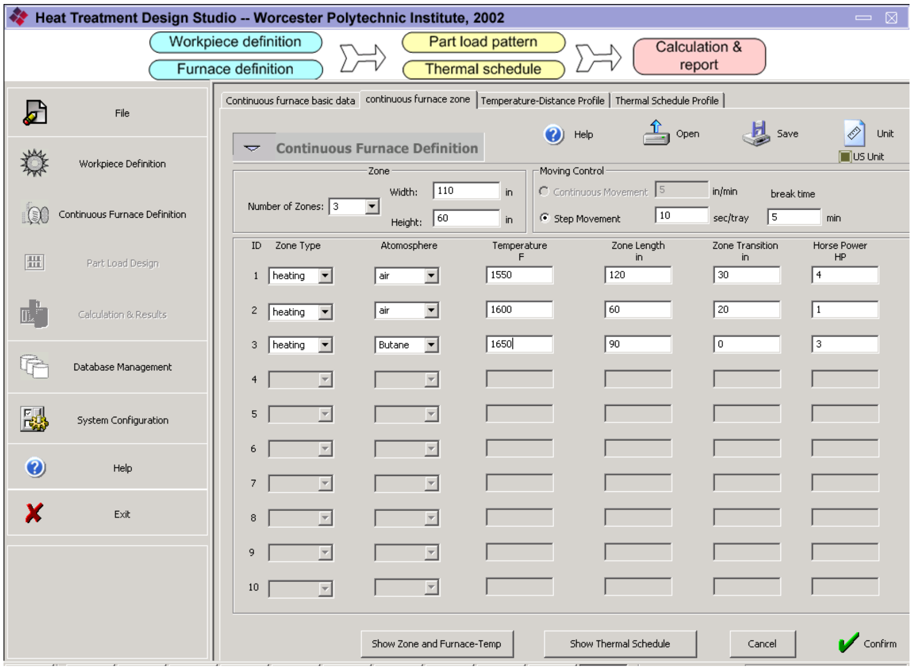
Fig. 47 Virtual fixture size definition for continuous furnace



Furnace Name: Pulse-controlled continuous furnace_3

Furnace Image: File not found.

Fig. 48 Continuous furnace definition 1



☑ US Unit

Zone

Number of Zones: 3

Width: 110 in

Height: 60 in

Moving Control

○ Continuous Movement 5 in/min

● Step Movement 10 sec/tray

break time 5 min

ID	Zone Type	Atomosphere	Temperature F	Zone Length in	Zone Transition in	Horse Power HP
1	heating	air	1550	120	30	4
2	heating	air	1600	60	20	1
3	heating	Butane	1650	90	0	3
4						
5						
6						
7						
8						
9						
10						

Fig. 49 Continuous furnace definition 2

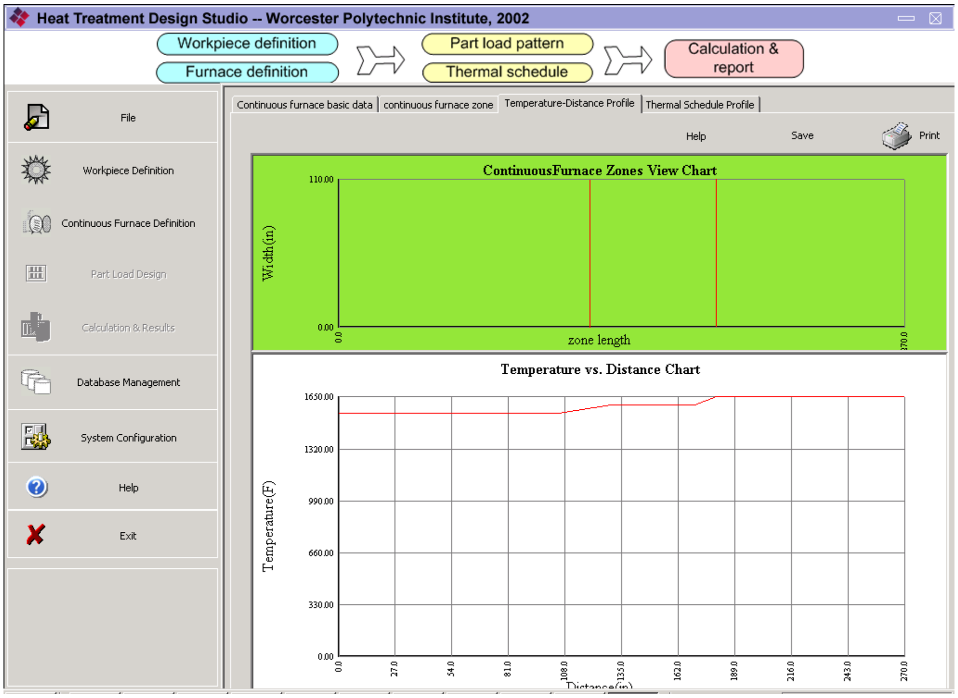


Fig. 50 Continuous furnace definition 3

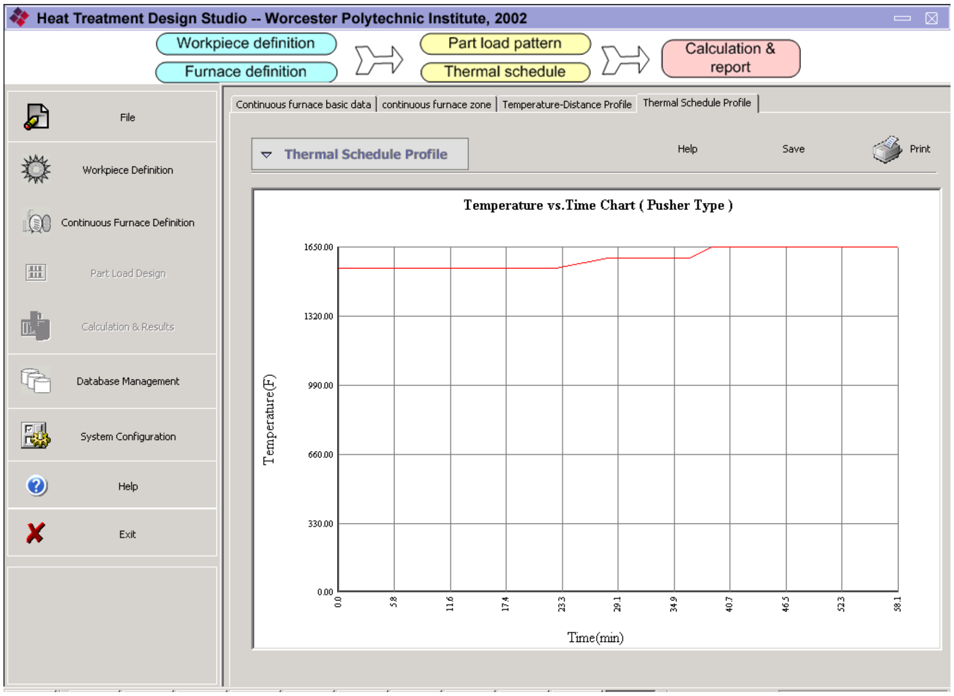
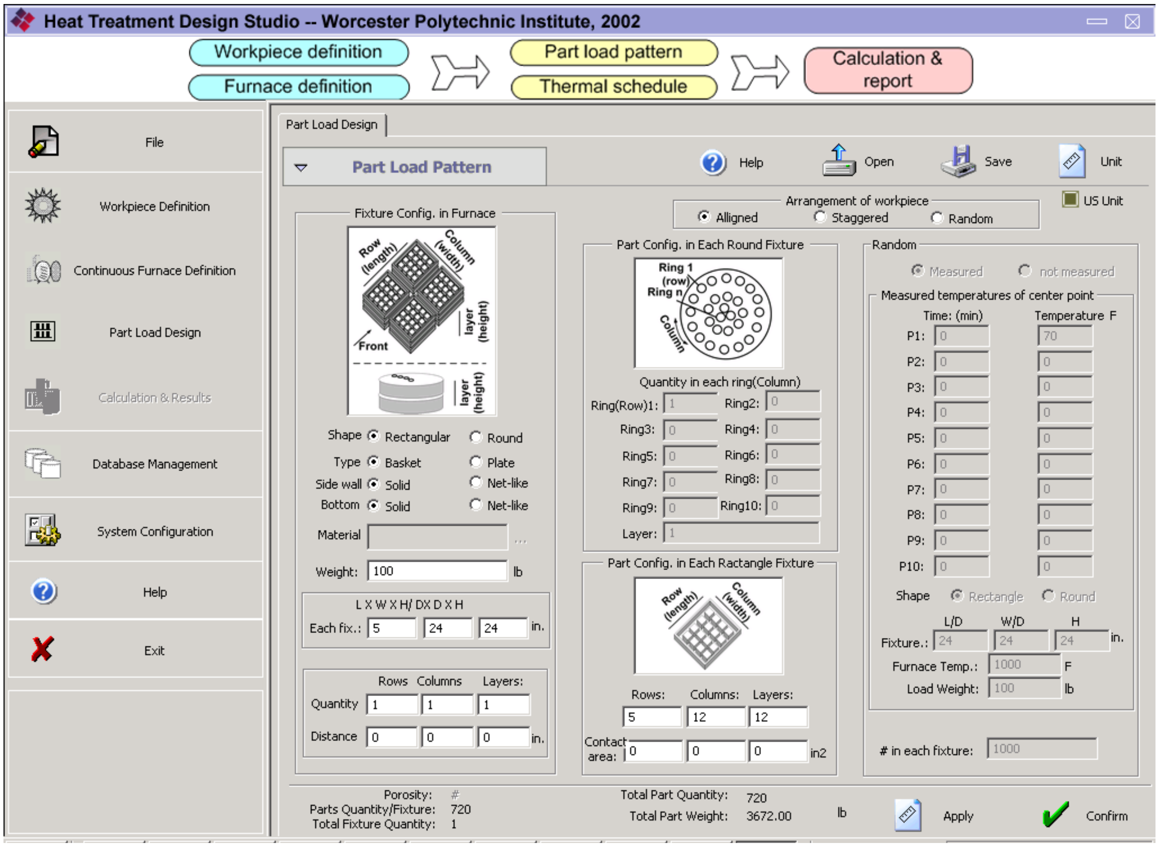


Fig. 51 Continuous furnace definition 4

6.3.3 Load Pattern Definition

Load pattern consists of fixture configuration and the part configuration. Fixture configuration consists of fixture shape and type. Part configuration consists of arrangement of workpiece in the fixture, which can be aligned, staggered and random. The load pattern definition is shown in Fig. 52.



Fixture Config. in Furnace

Shape ● Rectangular ○ Round

Type ● Basket ○ Plate

Side wall ● Solid ○ Net-like

Bottom ● Solid ○ Net-like

Material:

Weight: 100 lb

	L X W X H/ DX D X H			
Each fix.:	5	24	24	in.

	Rows	Columns	Layers:	
Quantity	1	1	1	
Distance	0	0	0	in.

Arrangement of workpiece: ● Alligned ○ Staggered ○ Random

☑ US Unit

Part Config. in Each Round Fixture

Quantity in each ring(Column)

Ring(Row)1:	1	Ring2:	0
Ring3:	0	Ring4:	0
Ring5:	0	Ring6:	0
Ring7:	0	Ring8:	0
Ring9:	0	Ring10:	0

Layer: 1

Part Config. in Each Ractangle Fixture

	Rows:	Columns:	Layers:	
	5	12	12	
Contact area:	0	0	0	in2

Random

● Measured ○ not measured

Measured temperatures of center point

	Time: (min)	Temperature F
P1:	0	70
P2:	0	0
P3:	0	0
P4:	0	0
P5:	0	0
P6:	0	0
P7:	0	0
P8:	0	0
P9:	0	0
P10:	0	0

Shape ● Rectangle ○ Round

	L/D	W/D	H	
Fixture.:	24	24	24	in.

Furnace Temp.: 1000 F

Load Weight: 100 lb

in each fixture: 1000

Porosity: #

Parts Quantity/Fixture: 720

Total Fixture Quantity: 1

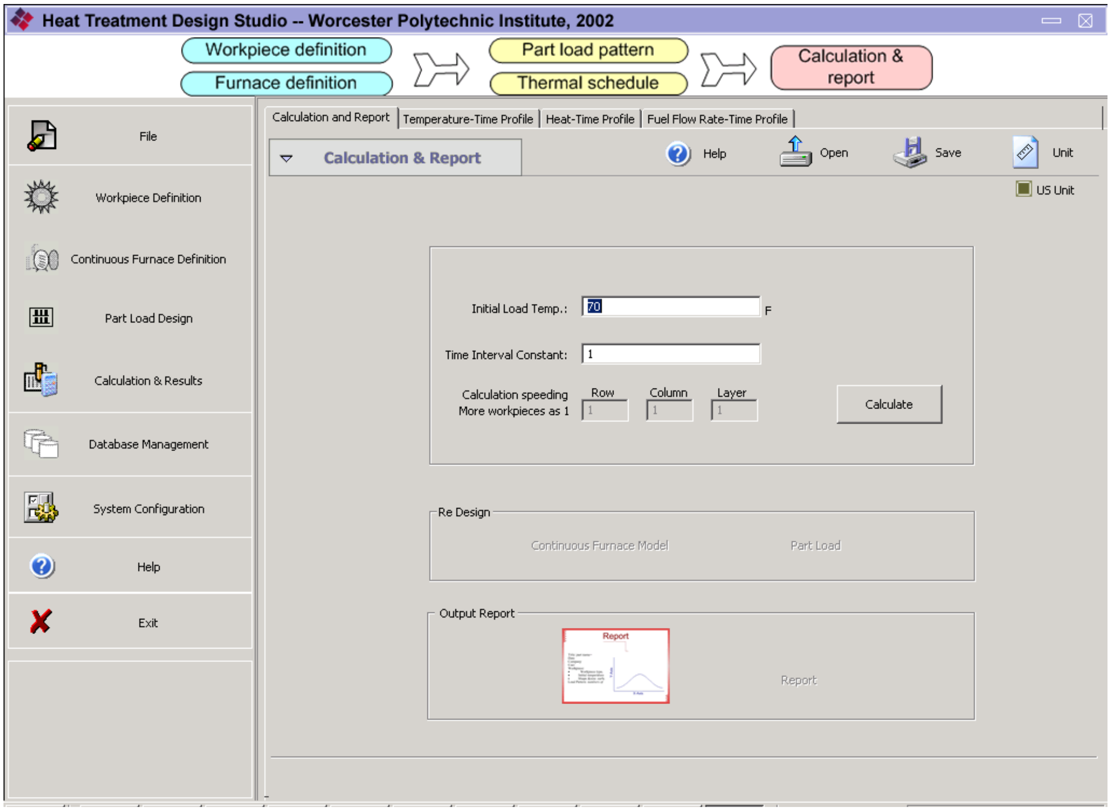
Total Part Quantity: 720

Total Part Weight: 3672.00 lb

Fig. 52 Load pattern definition

6.3.4 Results and Reports

The various results obtained from the system are shown in Fig. 53 and 54. Static curves include the set zone temperatures in the furnace, furnace temperature, fastest workpiece temperature, slowest workpiece temperature, and temperatures of the six centers of edges and faces.



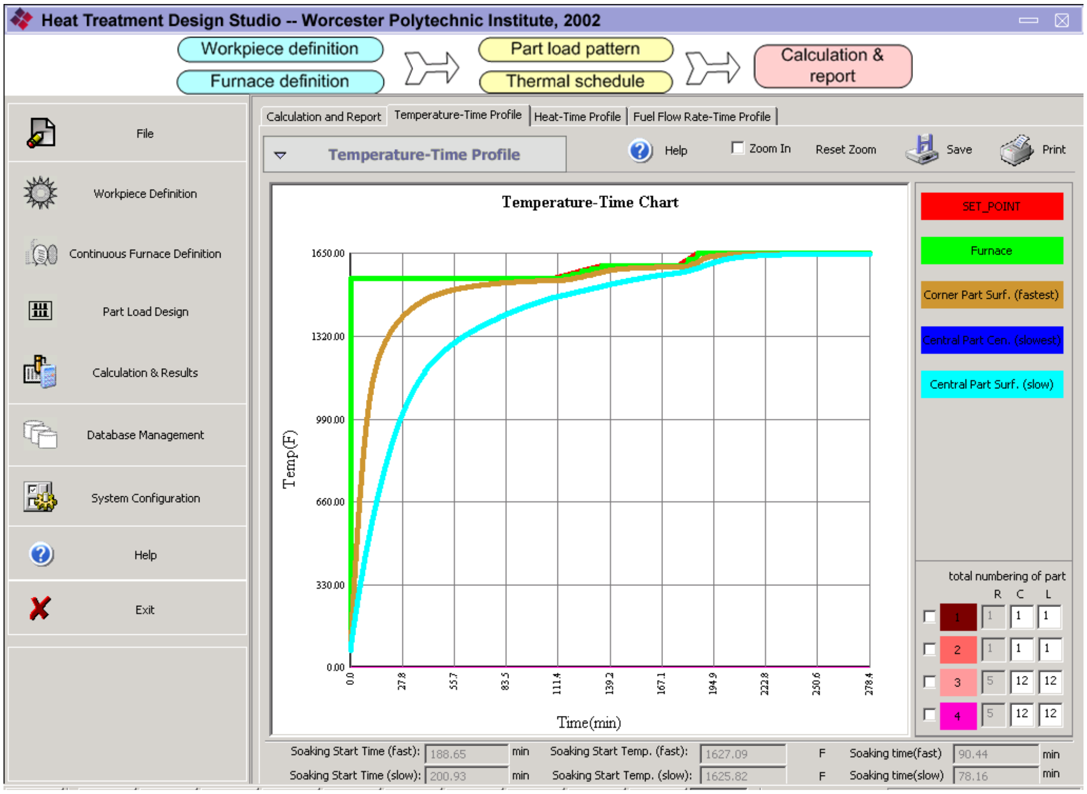
☑ US Unit

Initial Load Temp.: 70 F

Time Interval Constant: 1

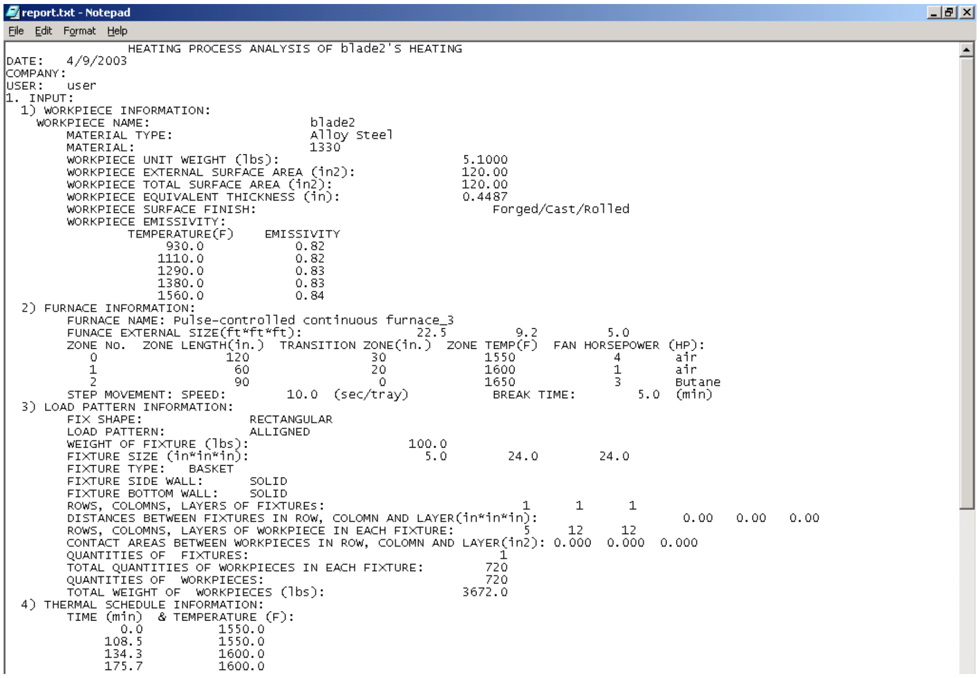
Calculation speeding More workpieces as 1: Row 1, Column 1, Layer 1

Fig. 53 Calculation page



Soaking Start Time (fast): 188.65 min
Soaking Start Temp. (fast): 1627.09 F
Soaking time(fast) 90.44 min
Soaking Start Time (slow): 200.93 min
Soaking Start Temp. (slow): 1625.82 F
Soaking time(slow) 78.16 min

Fig. 54 Temperature-time profile result

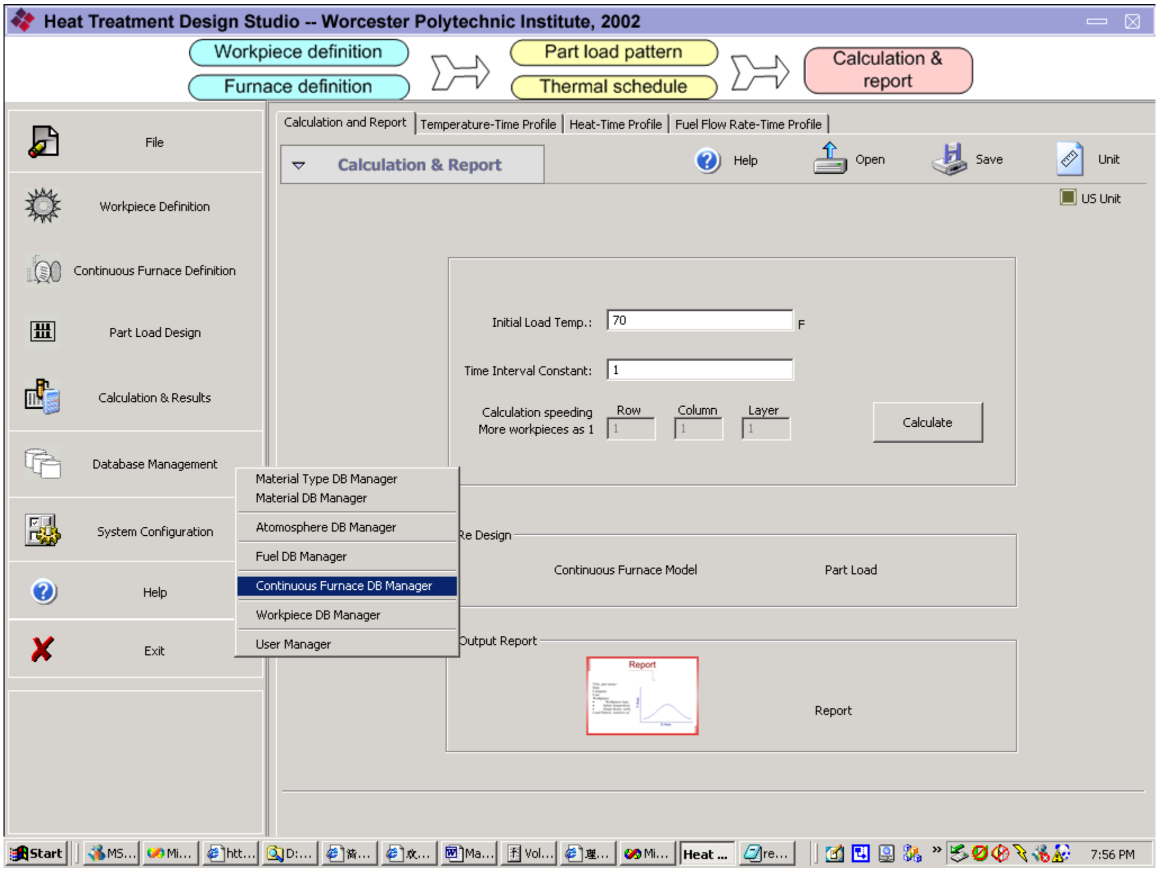


```
                HEATING PROCESS ANALYSIS OF blade2'S HEATING
DATE:    4/9/2003
COMPANY:
USER:    user
1. INPUT:
  1) WORKPIECE INFORMATION:
    WORKPIECE NAME:                            blade2
        MATERIAL TYPE:                         Alloy Steel
        MATERIAL:                              1330
        WORKPIECE UNIT WEIGHT (lbs):                             5.1000
        WORKPIECE EXTERNAL SURFACE AREA (in2):                   120.00
        WORKPIECE TOTAL SURFACE AREA (in2):                      120.00
        WORKPIECE EQUIVALENT THICKNESS (in):                     0.4487
        WORKPIECE SURFACE FINISH:                                    Forged/Cast/Rolled
        WORKPIECE EMISSIVITY:
                TEMPERATURE(F)    EMISSIVITY
                     930.0           0.82
                    1110.0           0.82
                    1290.0           0.83
                    1380.0           0.83
                    1560.0           0.84
  2) FURNACE INFORMATION:
        FURNACE NAME: Pulse-controlled continuous furnace_3
        FUNACE EXTERNAL SIZE(ft*ft*ft):                 22.5         9.2         5.0
        ZONE No.  ZONE LENGTH(in.)  TRANSITION ZONE(in.)  ZONE TEMP(F)  FAN HORSEPOWER (HP):
           0                120                   30           1550            4       air
           1                 60                   20           1600            1       air
           2                 90                    0           1650            3       Butane
        STEP MOVEMENT: SPEED:       10.0  (sec/tray)           BREAK TIME:        5.0  (min)
  3) LOAD PATTERN INFORMATION:
        FIX SHAPE:                RECTANGULAR
        LOAD PATTERN:             ALLIGNED
        WEIGHT OF FIXTURE (lbs):                     100.0
        FIXTURE SIZE (in*in*in):                       5.0        24.0        24.0
        FIXTURE TYPE:   BASKET
        FIXTURE SIDE WALL:        SOLID
        FIXTURE BOTTOM WALL:      SOLID
        ROWS, COLOMNS, LAYERS OF FIXTURES:                         1      1      1
        DISTANCES BETWEEN FIXTURES IN ROW, COLOMN AND LAYER(in*in*in):                0.00    0.00    0.00
        ROWS, COLOMNS, LAYERS OF WORKPIECE IN EACH FIXTURE:        5     12     12
        CONTACT AREAS BETWEEN WORKPIECES IN ROW, COLOMN AND LAYER(in2): 0.000  0.000  0.000
        QUANTITIES OF  FIXTURES:                                 1
        TOTAL QUANTITIES OF WORKPIECES IN EACH FIXTURE:        720
        QUANTITIES OF  WORKPIECES:                             720
        TOTAL WEIGHT OF  WORKPIECES (lbs):                  3672.0
  4) THERMAL SCHEDULE INFORMATION:
        TIME (min)  & TEMPERATURE (F):
             0.0          1550.0
           108.5          1550.0
           134.3          1600.0
           175.7          1600.0
```

Fig. 55 Report

6.3.5 Database Management

A separate interface is provided to manage the databases. These include several database management interfaces that could be accessed from the Database Management icon in the main page of the software (Refer Fig. 56). Apart from several existing databases a new database is created for the continuous furnace with several parameters to store the furnace information that enables us to directly use the furnace data from the software. A screen shot of the Continuous Furnace Interface is shown in Fig. 57.

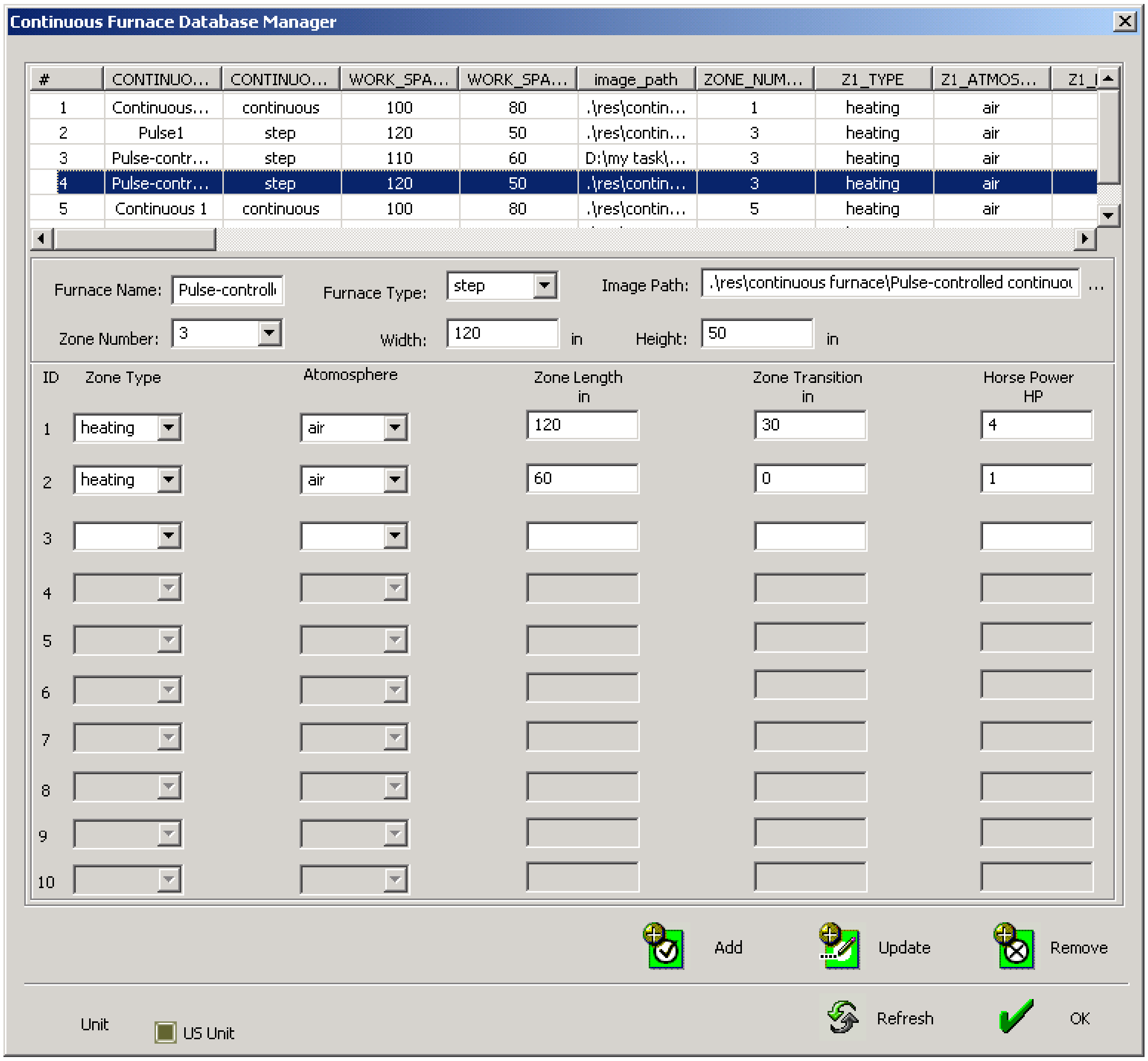


Initial Load Temp.: 70 F

Time Interval Constant: 1

Calculation speeding More workpieces as 1 — Row 1, Column 1, Layer 1

Fig. 56 Database management



#	CONTINUO…	CONTINUO…	WORK_SPA…	WORK_SPA…	image_path	ZONE_NUM…	Z1_TYPE	Z1_ATMOS…	Z1_I
1	Continuous…	continuous	100	80	.\res\contin…	1	heating	air	
2	Pulse1	step	120	50	.\res\contin…	3	heating	air	
3	Pulse-contr…	step	110	60	D:\my task\…	3	heating	air	
4	Pulse-contr…	step	120	50	.\res\contin…	3	heating	air	
5	Continuous 1	continuous	100	80	.\res\contin…	5	heating	air	

Furnace Name: Pulse-controlli
Furnace Type: step
Image Path: .\res\continuous furnace\Pulse-controlled continuou …
Zone Number: 3
Width: 120 in
Height: 50 in

ID	Zone Type	Atomosphere	Zone Length in	Zone Transition in	Horse Power HP
1	heating	air	120	30	4
2	heating	air	60	0	1
3					
4					
5					
6					
7					
8					
9					
10					

Unit ☑ US Unit

Fig. 57 Continuous furnace database management

CHAPTER 7. CASE STUDY ON CONTINUOUS FURNACE MODEL

The following case study was conducted on a Reciprocating Hearth Furnace, as shown in Fig. 58 for a stamped part that was loaded in a random pattern, as shown in Fig. 59. The various data for the furnace and the workpiece were acquired in the shop floor. Apart from the thermocouple measurements all other data were obtained, the furnace specifications and the workpiece details are given below,

7.1 Furnace Specifications

The Furnace seen in Fig. 58 is as Shaker furnace having four zones for the heating process

Fig. 58 Shaker Furnace used for the Case Study

Table 9. Furnace data

Furnace	Gas fired continuous shaker hearth furnace
Manufacture:	AGF
Model:	230E Reciprocating Hearth Furnace
Total size:	10' x 41" x 36"
Workspace:	78" x 12" x 3¼"
Number of zones -	4
Heating elements:	Total weight: 176 lbs
Capacity	Approx. 150 lbs/hr
Heating type	Gas fired
Fixture	Workpiece randomly loaded and fed by vibratory feeder

7.2 Workpiece Specifications

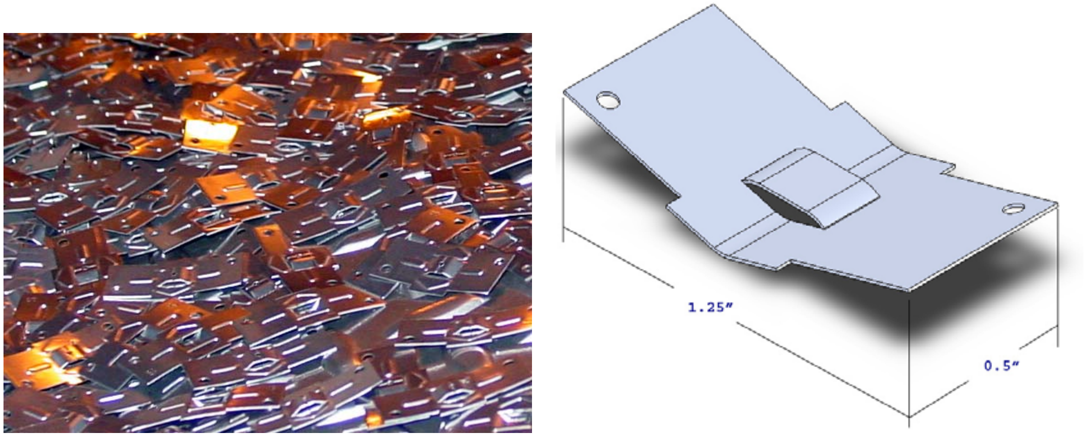


Fig. 59 Workpieces on the furnace and its dimensions

Table 10. Workpiece data

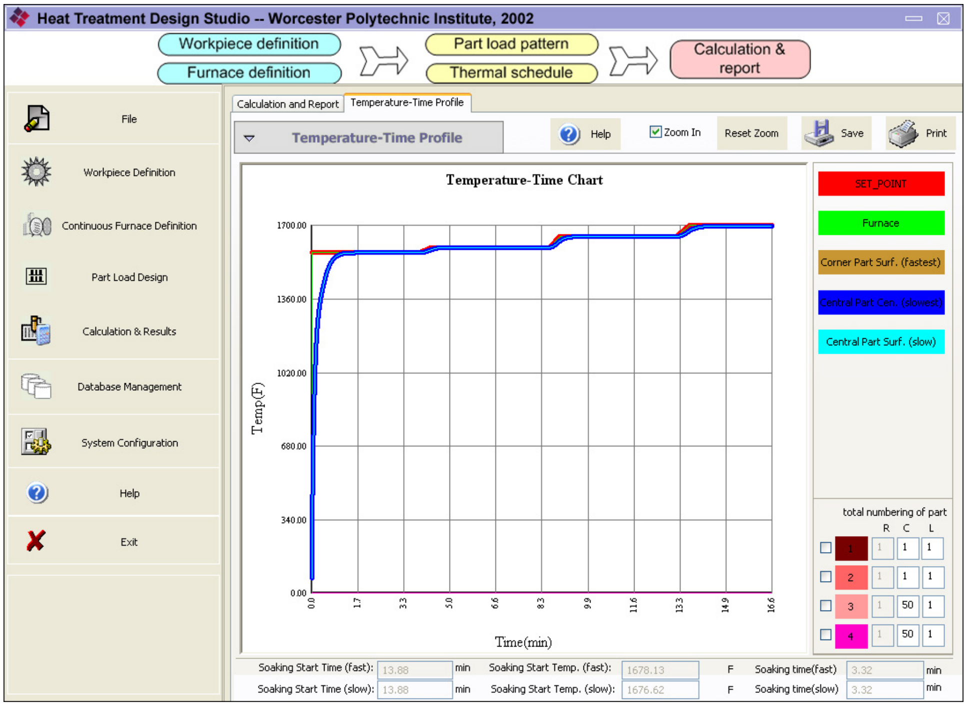
Workpiece Name:	Box type - 1.25” x 0.5” x 0.01
Material:	1050 Carbon Steel
Weight:	0.0035 lbs
Basic shape and size	See Figure 67

Table 11. Furnace temperature data

Zone	Temperature (F)	Atmosphere Content	Zone Length (inch)
1	1575	Endothermic gas	22.5
2	1600	Endothermic gas	25.5
3	1650	Endothermic gas	25.36
4	1700	Endothermic gas	18

7.3 Calculations

Based on the furnace and workpiece data and the temperature at different zones in the furnace, the temperature values of the load at different locations were calculated. The loading pattern is random in this case. The workpieces are arranged in rows and columns for the equivalent random load and the calculations were conducted. The screen shot of results obtained from the system are shown in Fig. 60. The Fig. 61 shows the temperature curves between of the set point temperature and the slowest part.



total numbering of part

		R	C	L
☐	1	1	1	1
☐	2	1	1	1
☐	3	1	50	1
☐	4	1	50	1

Soaking Start Time (fast): 13.88 min
Soaking Start Temp. (fast): 1678.13 F
Soaking time(fast) 3.32 min
Soaking Start Time (slow): 13.88 min
Soaking Start Temp. (slow): 1676.62 F
Soaking time(slow) 3.32 min

Fig. 60 The results obtained from system for the current case

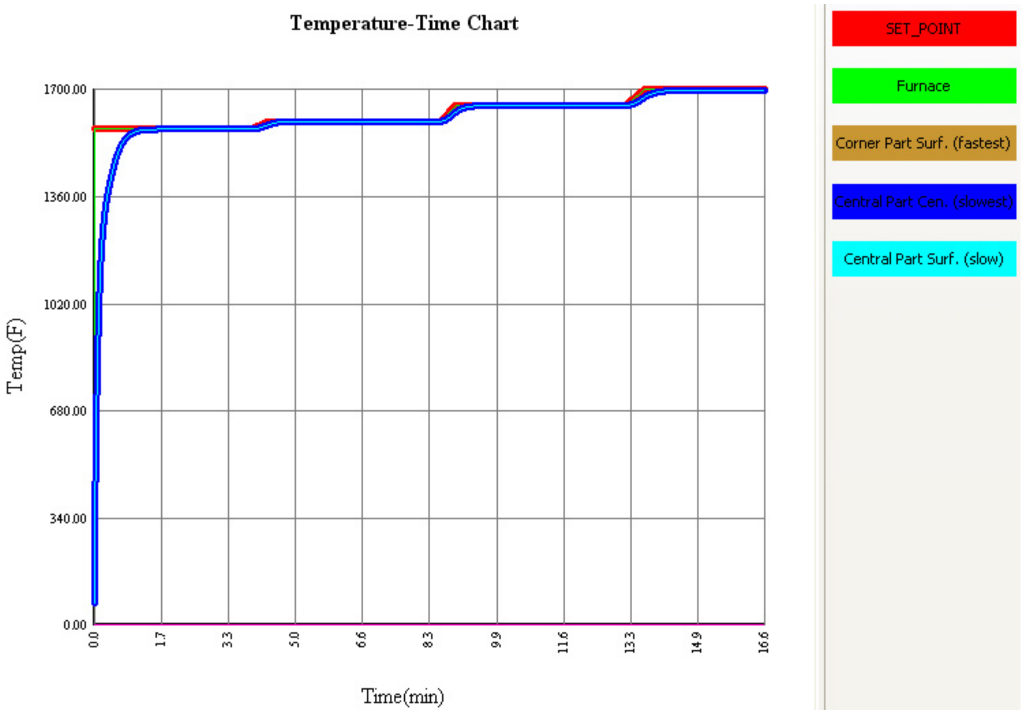


Fig. 61 Temperature curves obtained from system (Set point & Slowest curves)

7.4 Results and Conclusions

As observed from the Fig. 61 for the temperature curve of the slowest curve there is some room for improving the cycle time or the load pattern. But there are no measured results available at this time to verify the system and calculated results. The case study is to be continued. Once the data are obtained the system needs to be verified and further case studies are required to validate the system under different conditions.

CHAPTER 8. SUMMARY

This thesis presented a Computerized Heat Treatment for batch (CHT-*bf*) with the addition of random load model and for continuous furnace model CHT-*cf*. CHT is developed to assist the heat treatment process. The temperature distribution inside the furnace and the temperature of the various parts in the load can be determined. A number of case studies were presented for the validation of the models. The prediction results of workpiece temperature profiles are analyzed and compared with actual industrial results. In the thesis, the following work has been done,

1. Physics-mathematical models, based on the heat transfer theory, for the random loads were developed and various parameters are identified and classified.
2. There were basically two methods developed for the calculation of the effective thermal conductivity of the random loads.
3. Case studies were conducted in order to test the accuracy of the system and to check the random load model.
4. Further improvement was made in the database structure and the calculation process.
5. Mathematical model for the heat flow in the continuous furnace was developed.
6. A case study was conducted in order to check the system functionality of continuous furnace and to study what future work would be needed for the improvement of the system.

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